Re-viewing alloy compositions for selective laser melting

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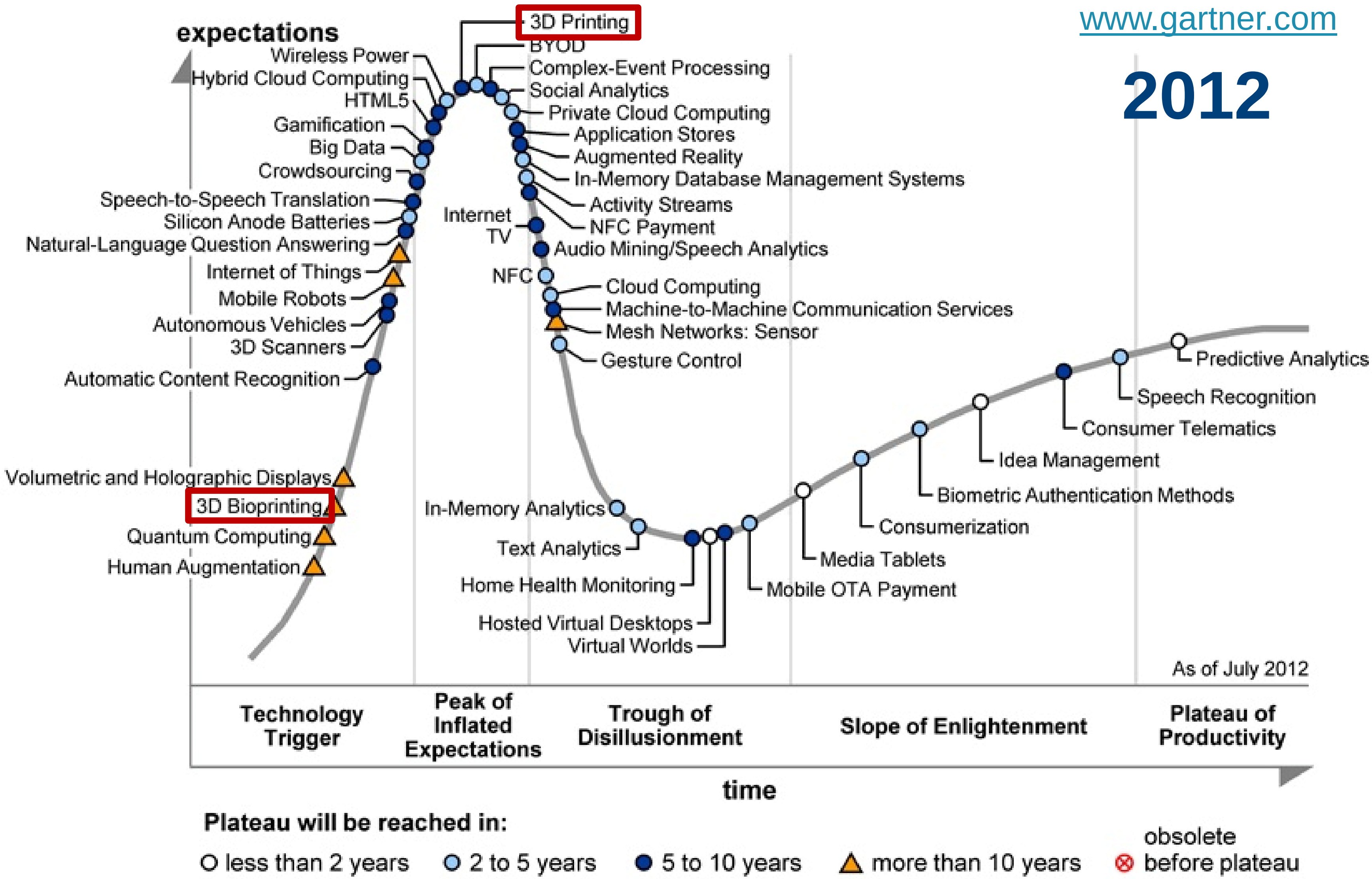
Hype vs Reality: Gartner Hype Cycle

www.gartner.com

2012



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Hype vs Reality: Gartner Hype Cycle

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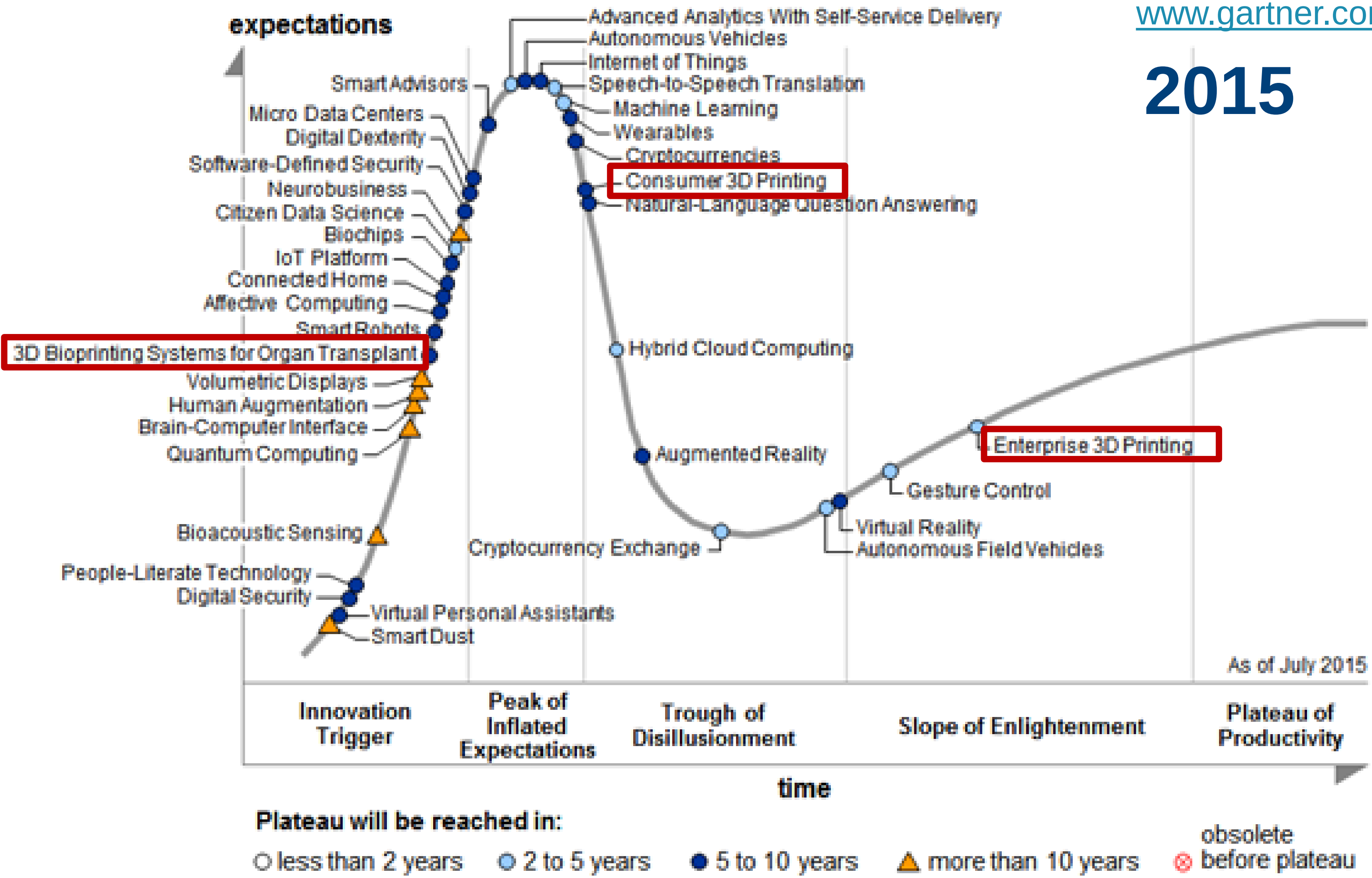
2015



Hype vs Reality: Gartner Hype Cycle

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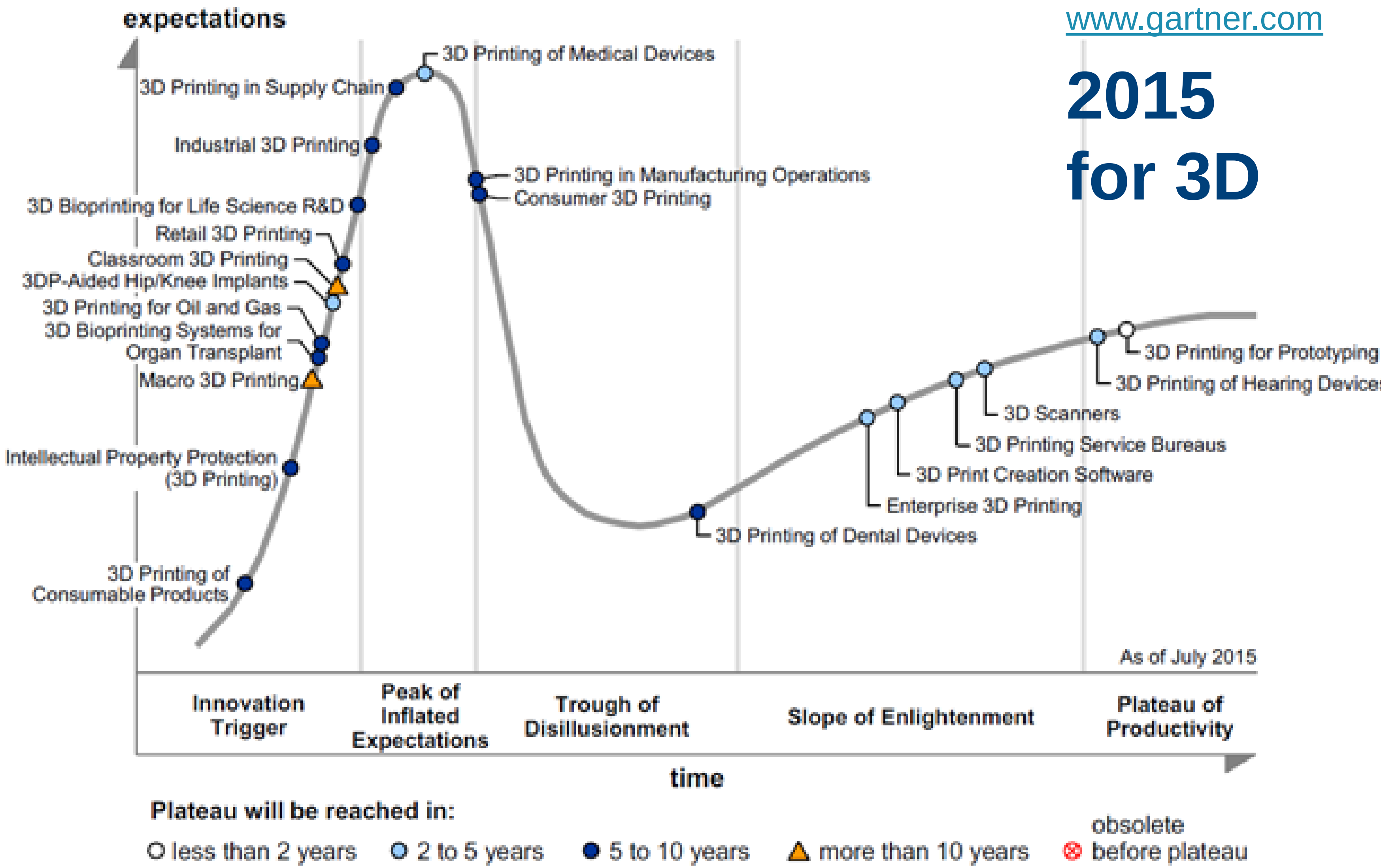
2015 for 3D



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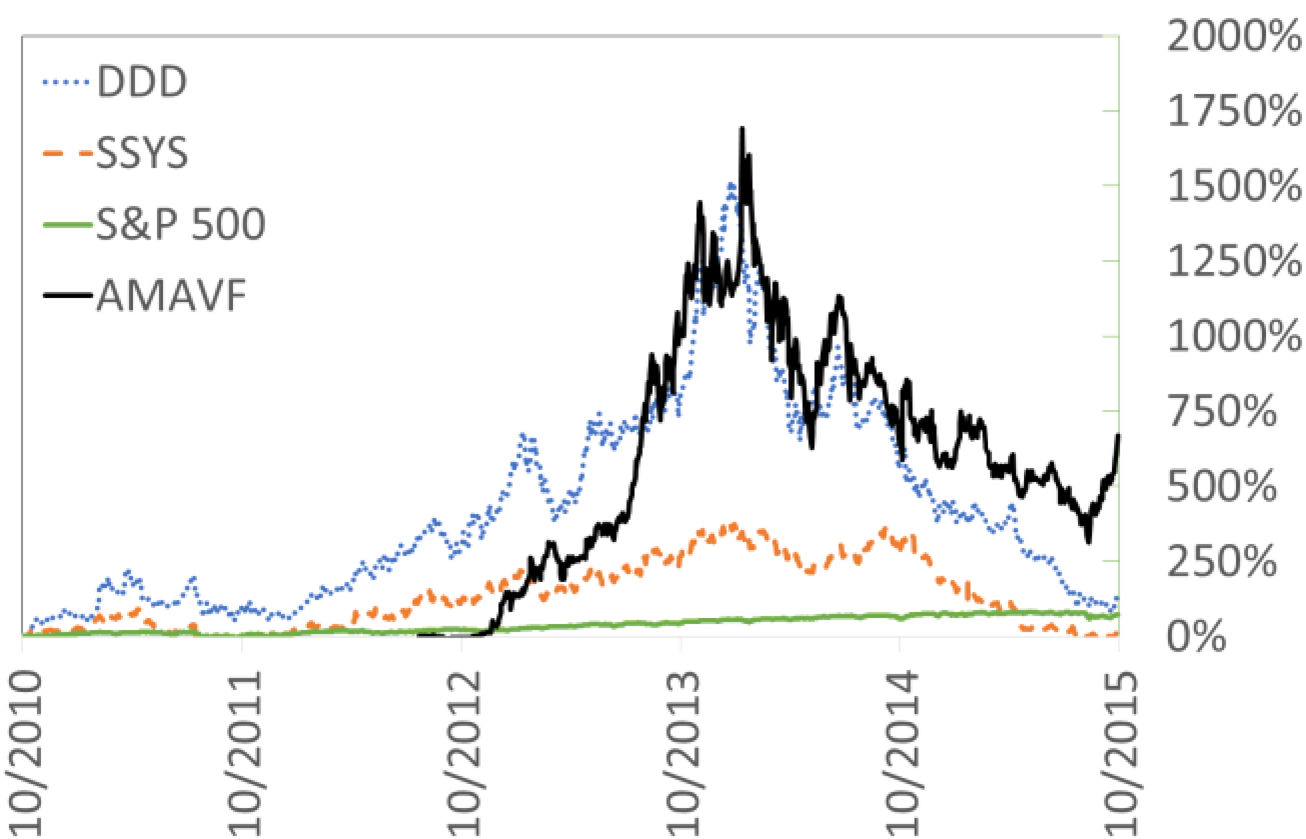
Hype vs Reality: 3D Printing Stock Bubble

- Overpriced
- Dissapointing earnings
- Increasing competition



Exploring the capabilities of AM

✓Design opportunities

BUT

- High internal stresses
- Porosity
- Cracks

BUT

✓Material opportunities

✓ New microstructures, phases, precipitates, …

Exploring the capabilities of AM

<u>**Change of mindset**</u>

- Is the existing material actually most suitable?
- Do we really need to use prealloyed powder?
- What microstructure and properties are required?

Example: Elemental Ti, Al and V mix

- Laser Metal Deposition (LMD)
- Good strength
- High ductility

- Less alloying elements compared to Ti6Al4V

Number	Composition	Oxygen content of powder (wt%)	K (σ_b/HV)	HV (Measured)	HV_y	σ_b (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)	ψ (%)
1#	Al: 2.4; V: 1.4	0.07	2.88	/	257.0	740	665	18.0	53.0
2#	Al: 4.1; V: 1.5	0.07	2.90	293.9	290.0	840	770	15.0	43.5
3#	Al: 3.2; V: 2.1	0.07	3.01	/	278.5	840	780	18.0	55.0
4#	Al: 4.3; V: 2.8	0.07	3.00	/	308.9	930	845	14.0	43.0
5#	Al: 4.5; V: 3.3	0.07	2.93	323	320.3	940	885	9.0	39.0
6#	Al: 4.9; V: 3.2	0.07	2.97	/	327.7	975	880	11.0	28.0
7#	Al: 3.8; V: 4.0	0.07	[illegible]	[illegible]	[illegible]	900	830	13.5	42.0
8#	Al: 5.0; V: 4.0	0.07	[illegible]	[illegible]	[illegible]	970	895	13.0	/
9#	Al: 2.9; V: 5.8	0.07	2.93	331.3	329.5	965	885	13.5	40.0
10#	Al: 5.1; V: 6.3	0.07	2.93	380.2	375.8	1100	1030	7.3	18.0
11#	Al: 7.2; V: 4.9	0.07	2.89	402.5	398.0	1150	1070	8.5	/
12#	Ti-6Al-4V	0.20	2.94	408	/	1200	1140	6.0	18.5
13#	TA15	0.13	2.98	400	/	1190	1100	7.5	13.0
14#	Ti60	/	3.0	420	/	1260	1150	7.0	12.0
15#	TC21	/	3.04	420	/	1250	1170	5.0	/
Ti-6Al-4V wrought standard (ASTM-B381-05)						≥895	≥828	≥8.0	≥25.0

UTS [MPa]
Yield [MPa]
ε [%]

Tan Hua et al., "*Microstructure and Mechanical properties of laser solid formed Ti-6Al-4V from blended elemental powders*", Rare Materials and Engineering 2009, 38(4):0574-0578

Lecture content

1. Different post processing for SLM produced materials
    - Ti6Al4V
    - AlSi10Mg
    - 18Ni300 Maraging Steel

2. Different composition to improve properties
    - Ti6Al4V + Mo
    - AlSi10Mg + Cu

3. Different composition to improve processability
    - Al7075 + Si

4. Different processing parameters for the same material

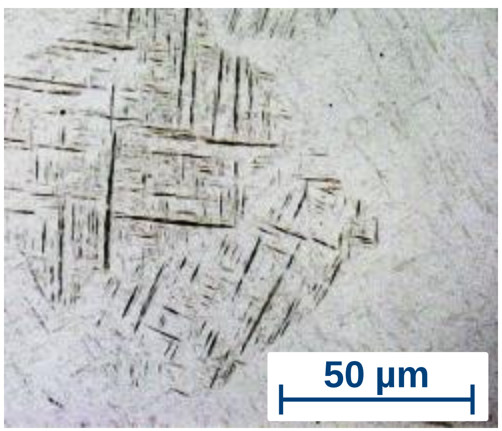
1

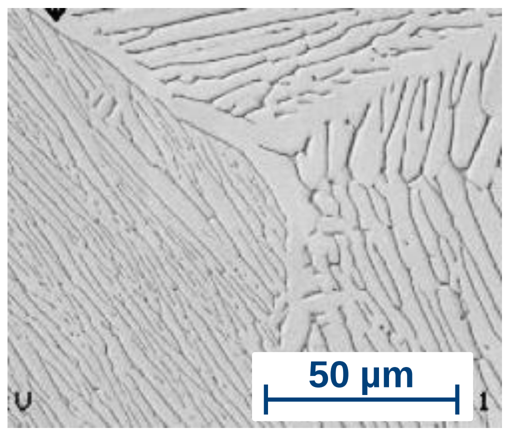
Post Processing of AM Material

Case 1: Ti6Al4V

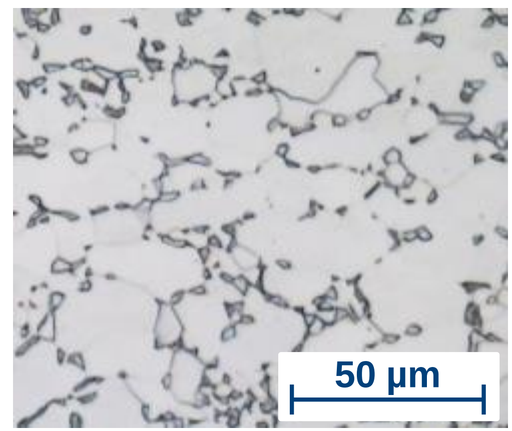
Different starting microstructure for SLM compared to other processes

SLM	**Cast**	**Wrought**
α‘ Martensite	α+β Lamellar	α+β Equiaxed





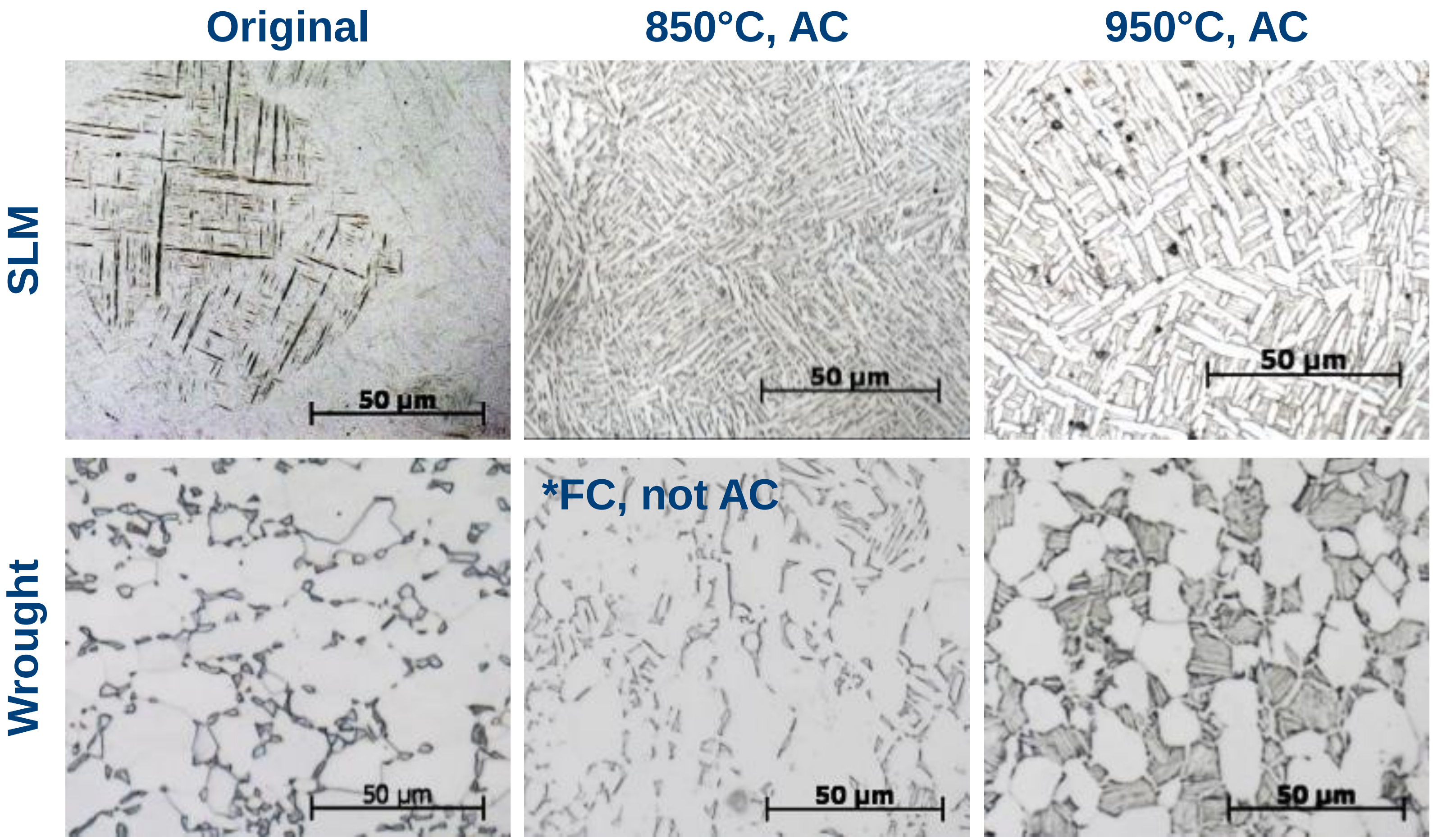
Pederson (2012)



B Vrancken, L Thijs, J-P Kruth, J Van Humbeeck, “*Heat treatment of Ti6Al4V produced by Selective Laser Melting: microstructure and mechanical properties*” JALCOM 541 (2012) 177-185

Case 1: Ti6Al4V

Different response to heat treatment caused by different α+β phase distribution

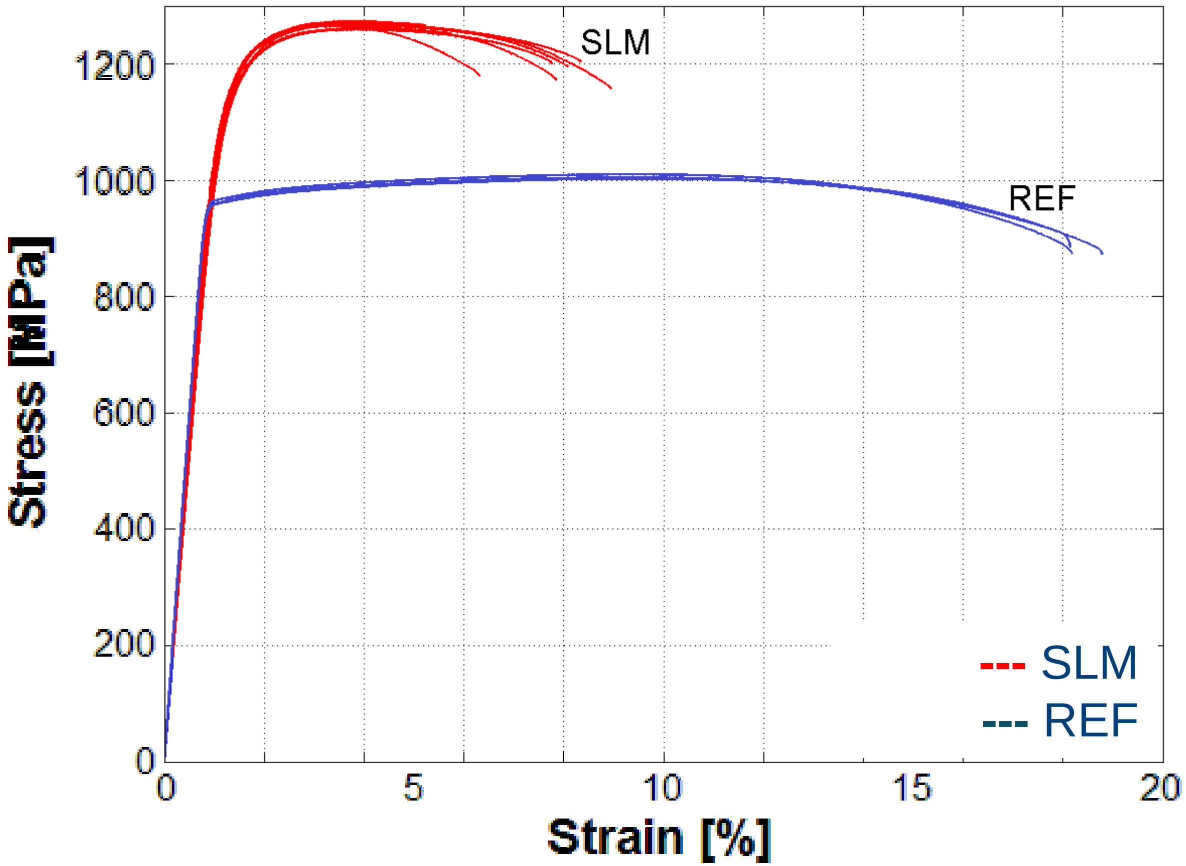


Improvement via **heat treatment**

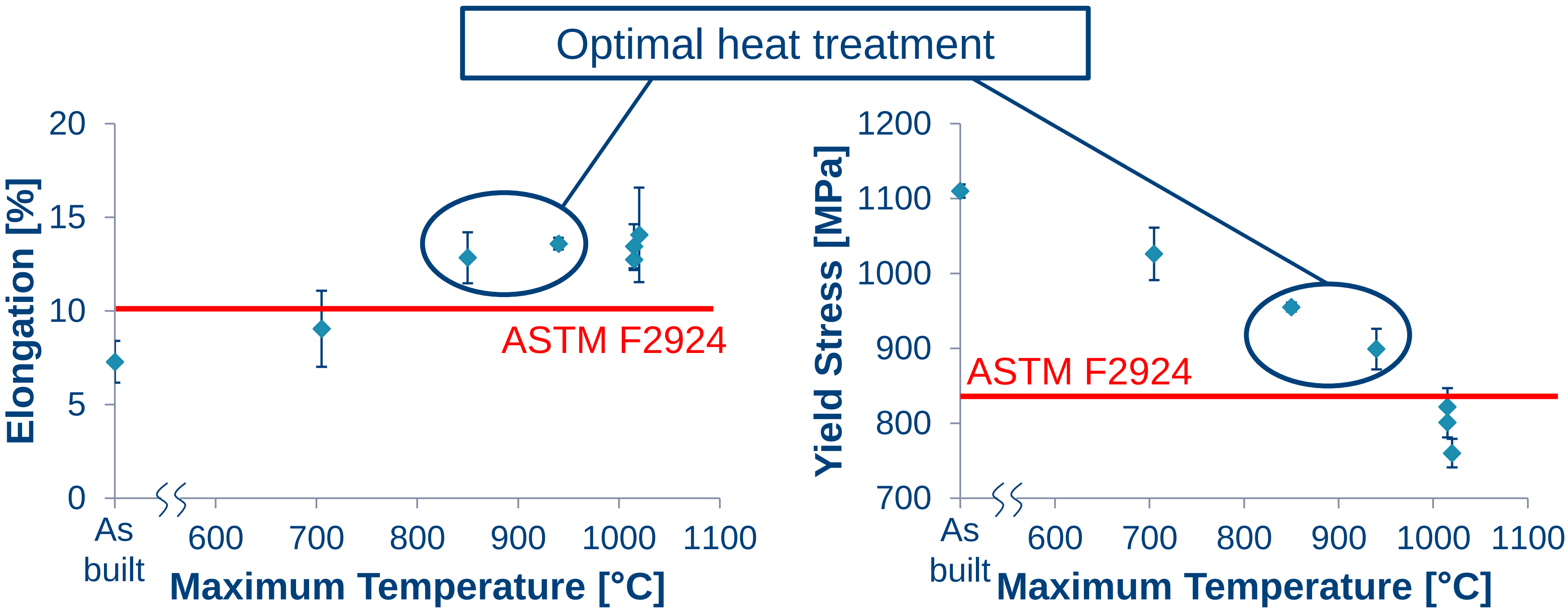
Maximum heat treatment temperature

→ Ductility increases, strength decreases with increasing temperature

- As built
- 705°C
- 843°C
- 940°C
- 1015°C



Case 1: Ti6Al4V



2-4h

850°C — **950°C**

Furnace cooling — **Air cooling**

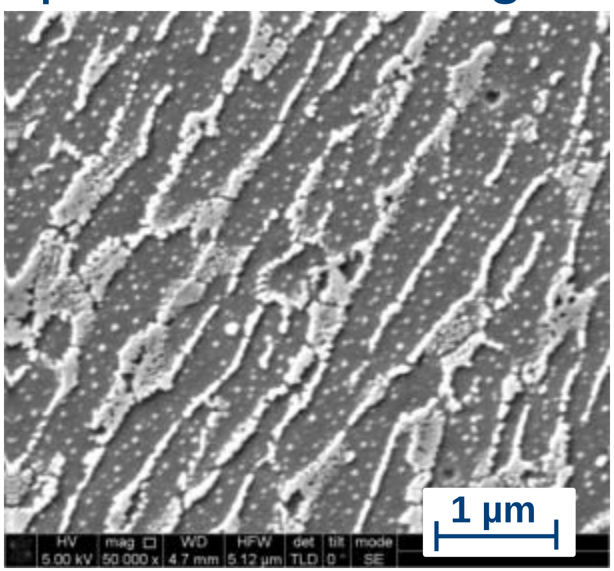
Case 2: AlSi10Mg

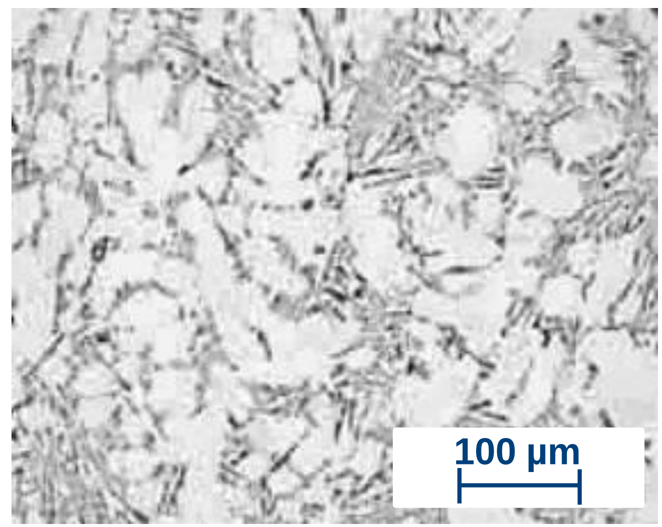
SLM

- Fine, cellular primary Al
- Intercellular Si
- Less than equilibrium 24 vol% eutectic → Supersaturated Al grains

Cast

- Large, dendritic primary Al
- Eutectic zones of Al+Si





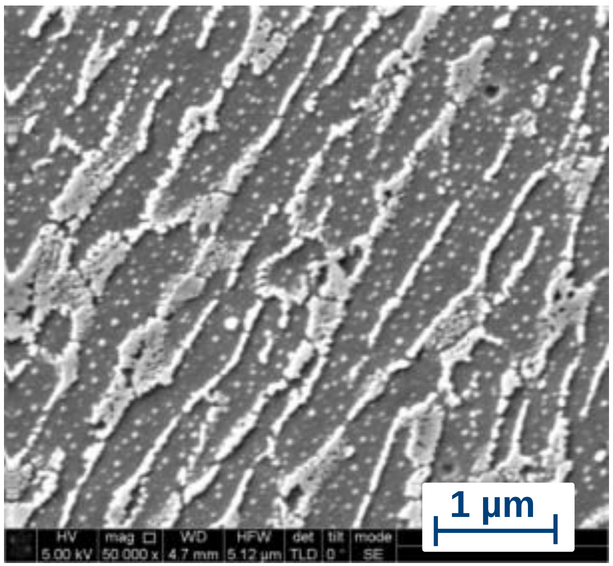
Bassani (2005)

L. Thijs, K. Kempen, J.P. Kruth, J. Van Humbeeck, “*Fine-structures aluminium products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder*”, Acta Mat., 61 (2013) 1809-1819

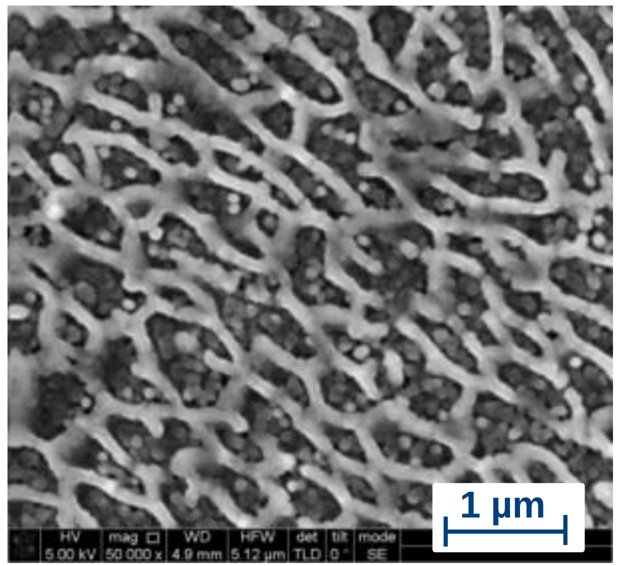
Case 2: AlSi10Mg

- Aging induced precipitation of Si inside Al grains
- Unrecoverable loss of fine structure after annealing

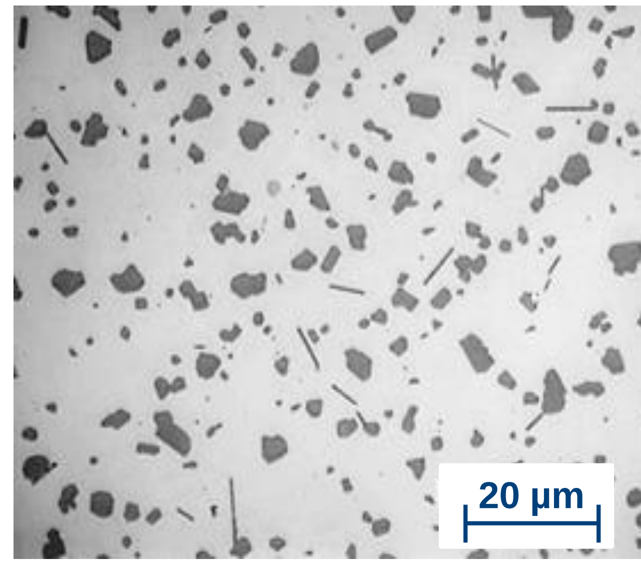
As built



Aged (175°C, 8h)



Annealed (540°C, 8h)



Hardness [HV]

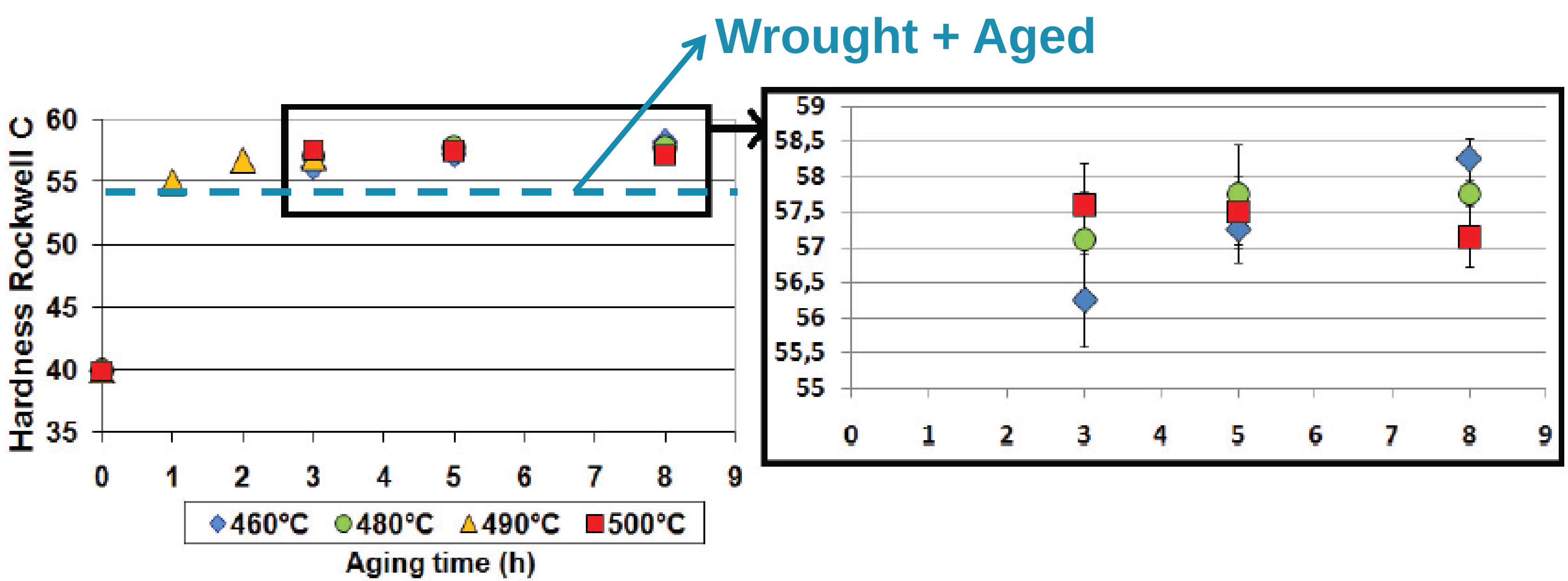
SLM	SLM + aging (175°C for 1h)	SLM + anneal + aging	HPDC	HPDC+ T6
124-128	148-154	110-115	95-105	130-133

Case 3: 18Ni300 maraging steel

- Hardness increase by 40% with optimal aging parameters

  → 480°C, 5h, AC

- Overaging at higher temperature (500°C) due to austenite reversion



K. Kempen, E. Yasa, L. Thijs, J. Van Humbeeck, J.P. Kruth, "*Microstructure and mechanical properties of Selective Laser Melted 18Ni-300 steel*", Physics Procedia, 12 (2011) 255-263

Case 3: 18Ni300 maraging steel

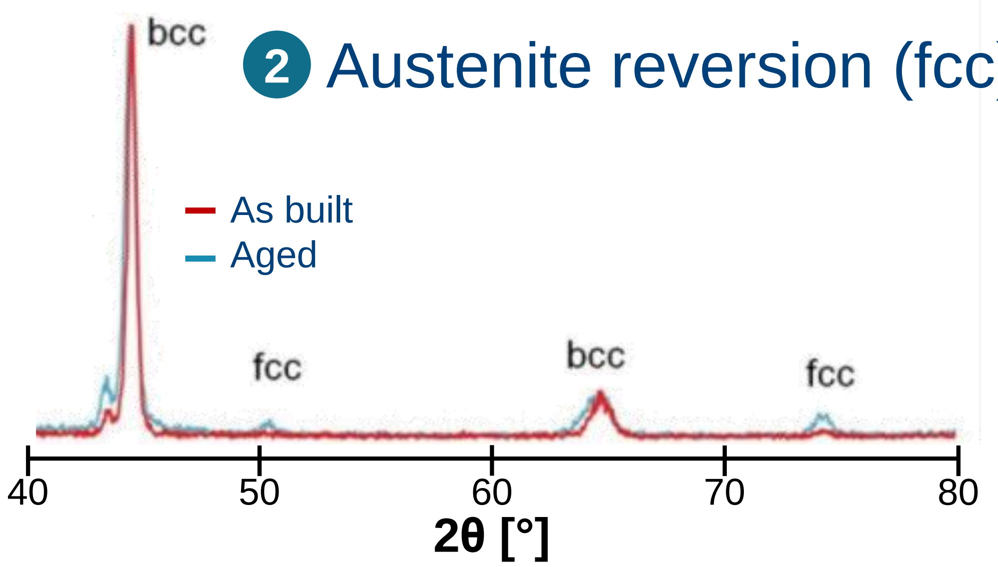
0 Supersaturated, fine, metastable martensite (bcc)

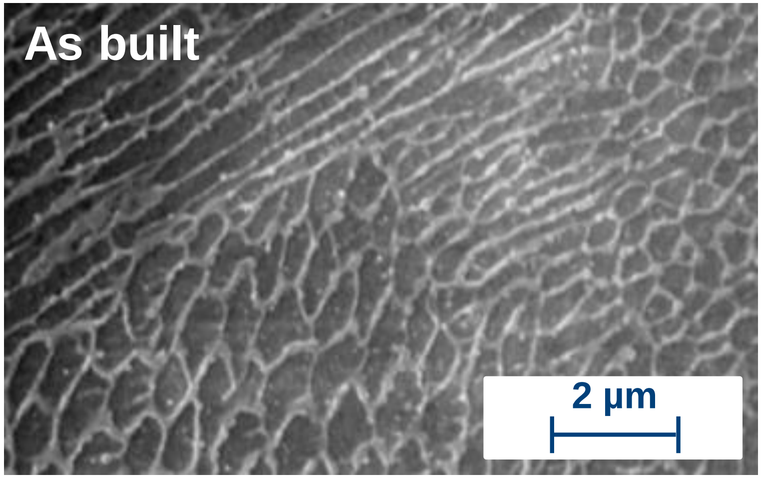
1 Precipitation of $(Fe,Ni,Co)_6Mo_7$

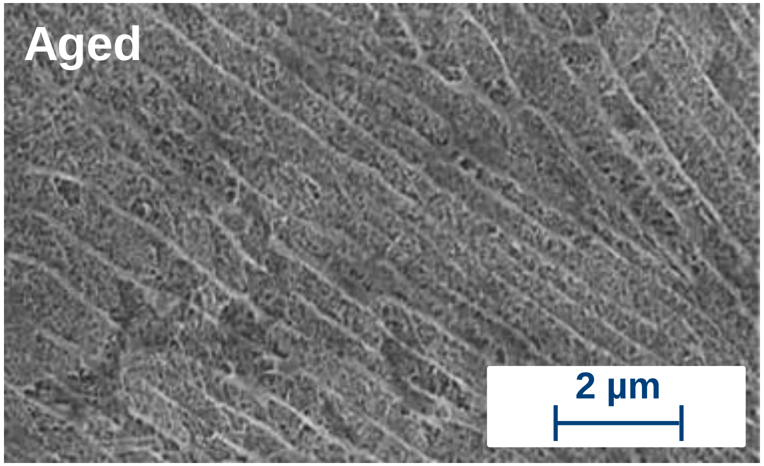
$(Fe,Ni,Co)_3Ti$

$(Fe,Ni,Co)_3Mo$

2 Austenite reversion (fcc)







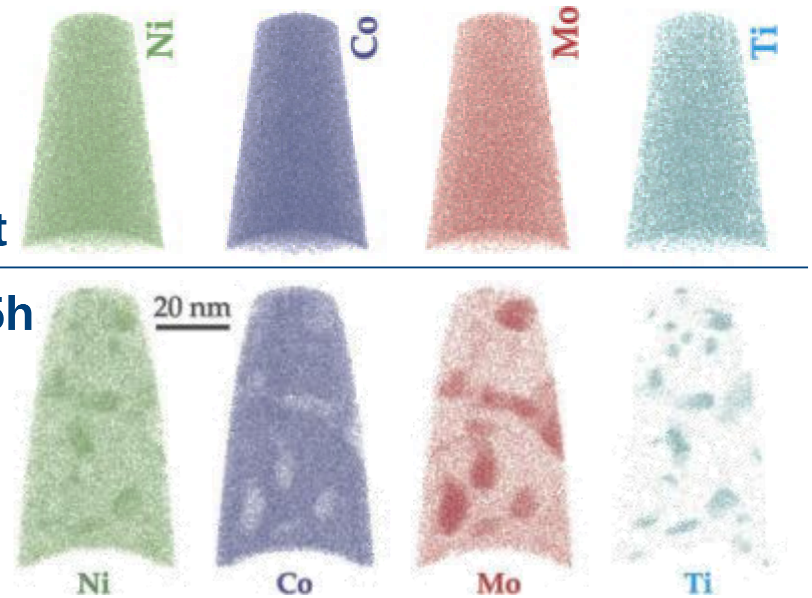
Case 3: 18Ni300 maraging steel

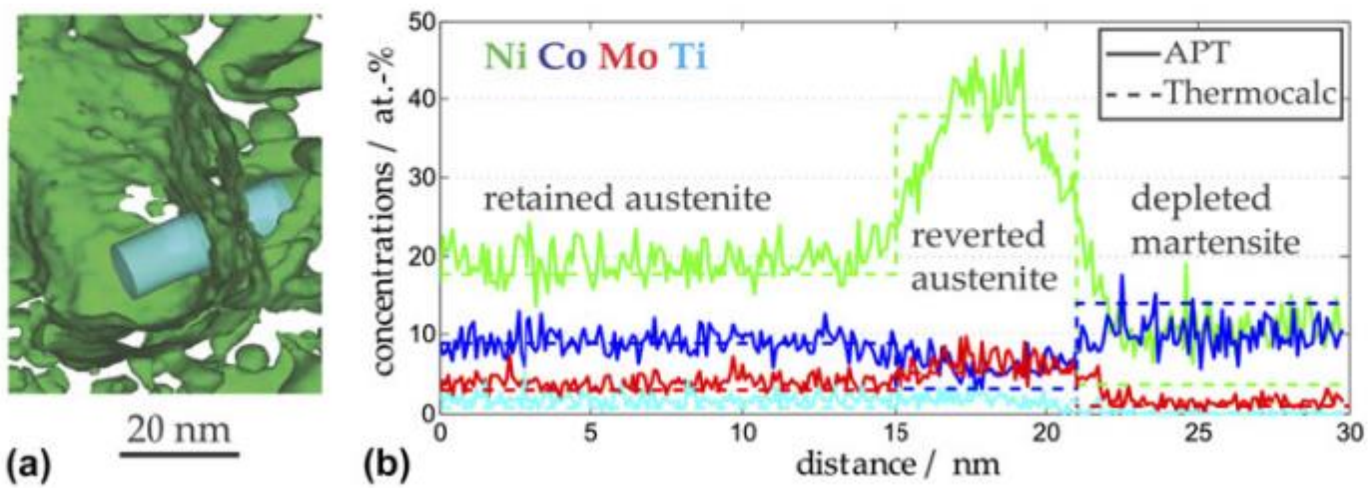
- Nanoscale precipitates lead to hardening

- Overaging by excessive austenite reversion

As built

480°C, 5h





E. Jägle, P-P. Choi, J. Van Humbeeck, D. Raabe, "*Precipitation and austenite reversion behavior of a maraging steel produced by selective laser melting*" J. Materials Research, 29(17) (2014) 2072-2079

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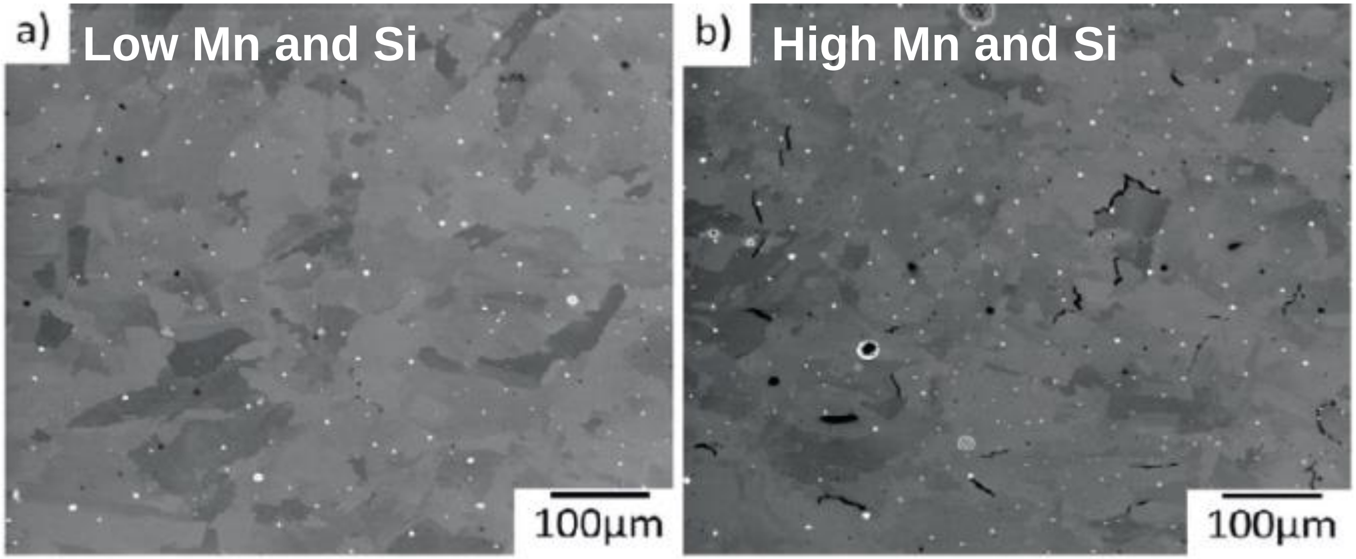
Alloying to improve properties

Example 1: Hastelloy X

Reducing the amount of Mn+Si reduces cracking (but slightly increases porosity)

- Theory: Low melting point phases and brittle intermetallics at grain boundaries



D. Tomus et al, "*Controlling the microstucture of Hastelloy-X-components manufactured by Selective Laser Melting*", Physica Pocedia 41 (2013) 823-827

Example 2: Hastelloy X

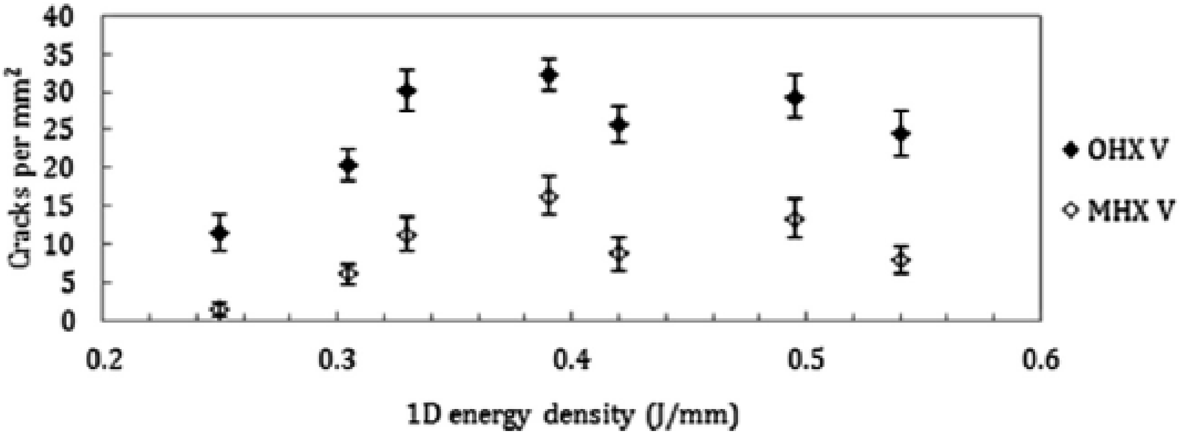
Increasing thermal shock resistance $$\tau = \frac{\sigma_{UTS} \cdot \kappa \cdot (1-\nu)}{E \cdot \alpha_{CTE}}$$

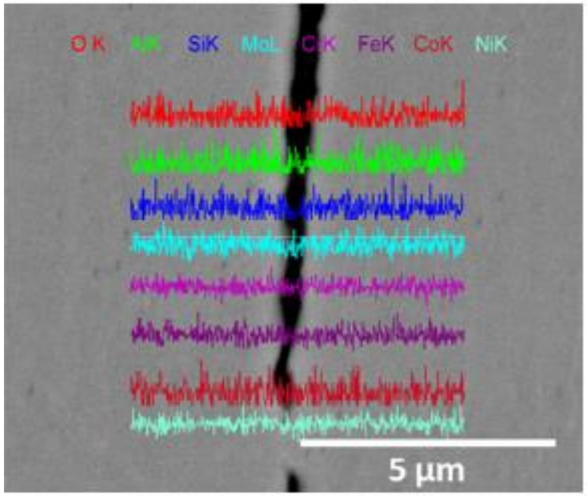
→ Increasing high temperature yield strength

→Change the composition within the specs

BUT

→ Lower high temperature ductility





N. Harrison et al, “*Reduction of micro-cracking in nickel superalloys processed by Selective Laser Melting: A fundamental alloy design approach*”, Acta Materialia 94 (2015) 59-68

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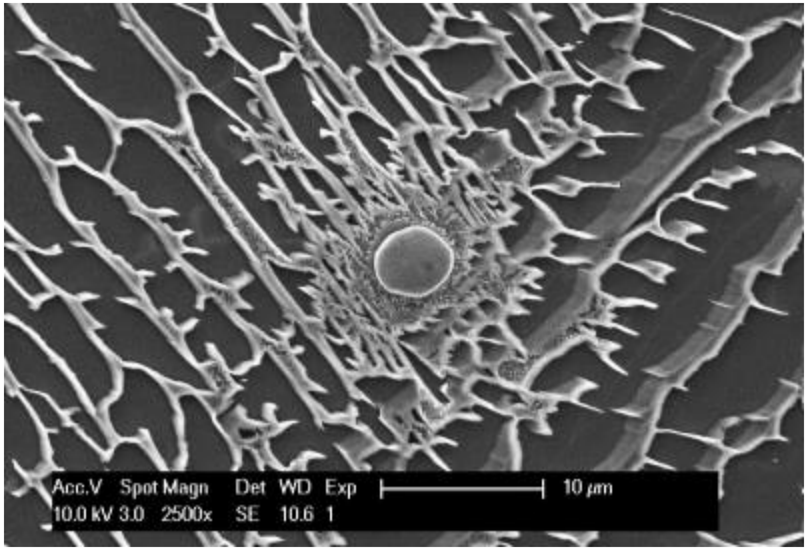
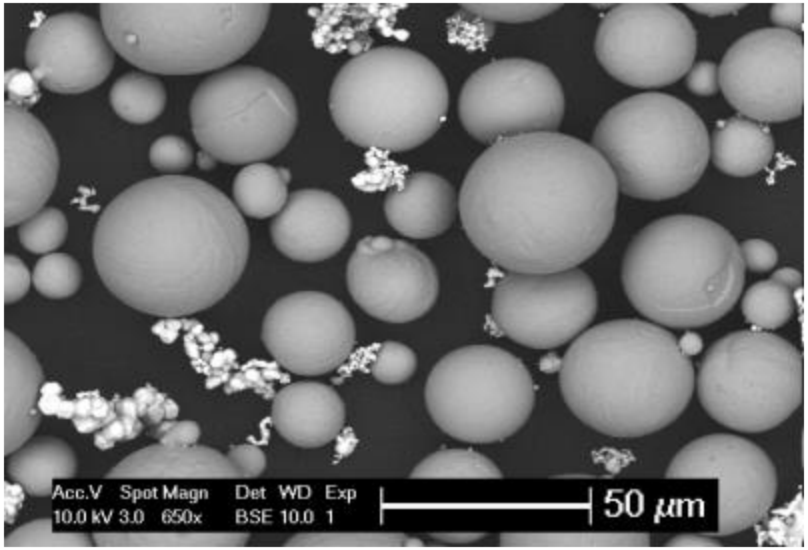
Example 3: Ti6Al4V+10Mo



One Mo particle in Ti6Al4V matrix after heat treatment

Effect of more than one particle?

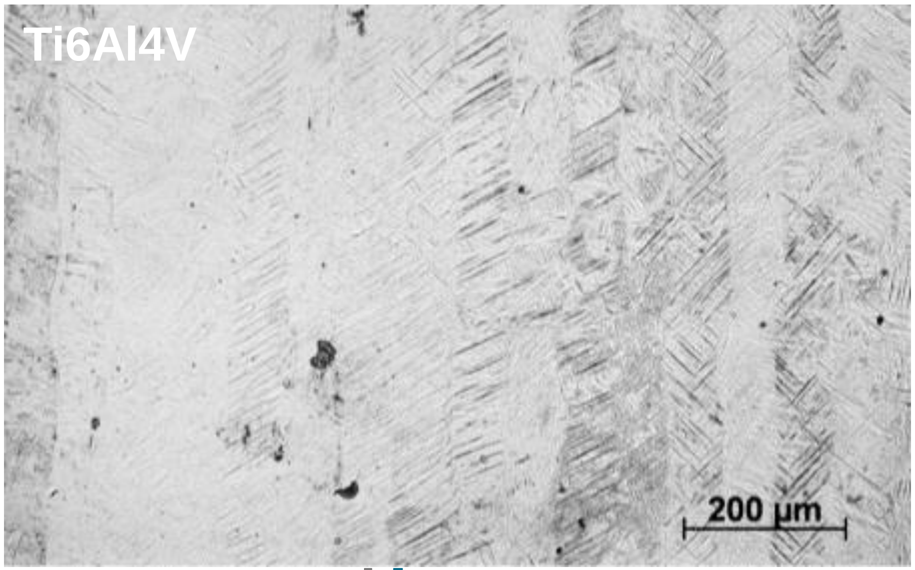


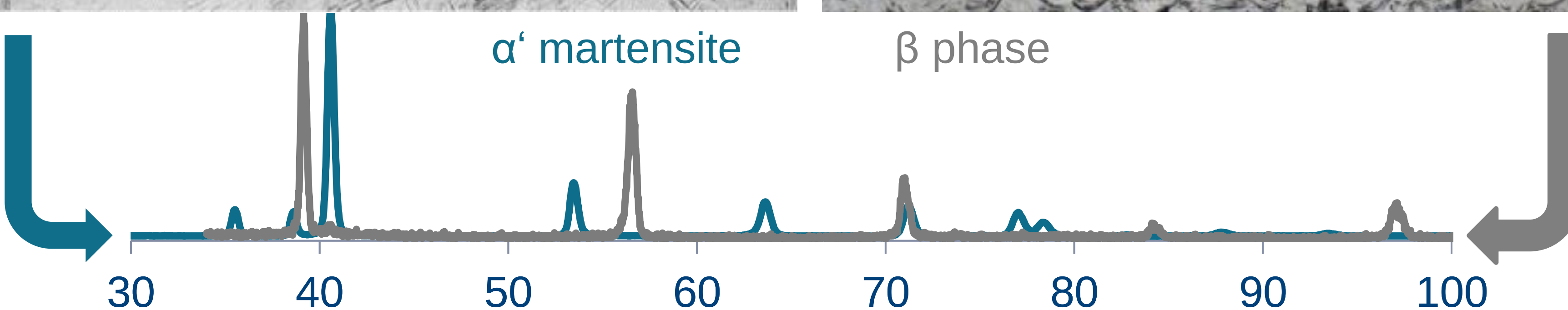
Ti6Al4V powder (spherical) with 10wt% Mo powder

- Stabilizes β phase
- 10wt% enough to maintain metastable β after quenching

Ti6Al4V+10Mo: Change in microstructure

And in crystal phase after production



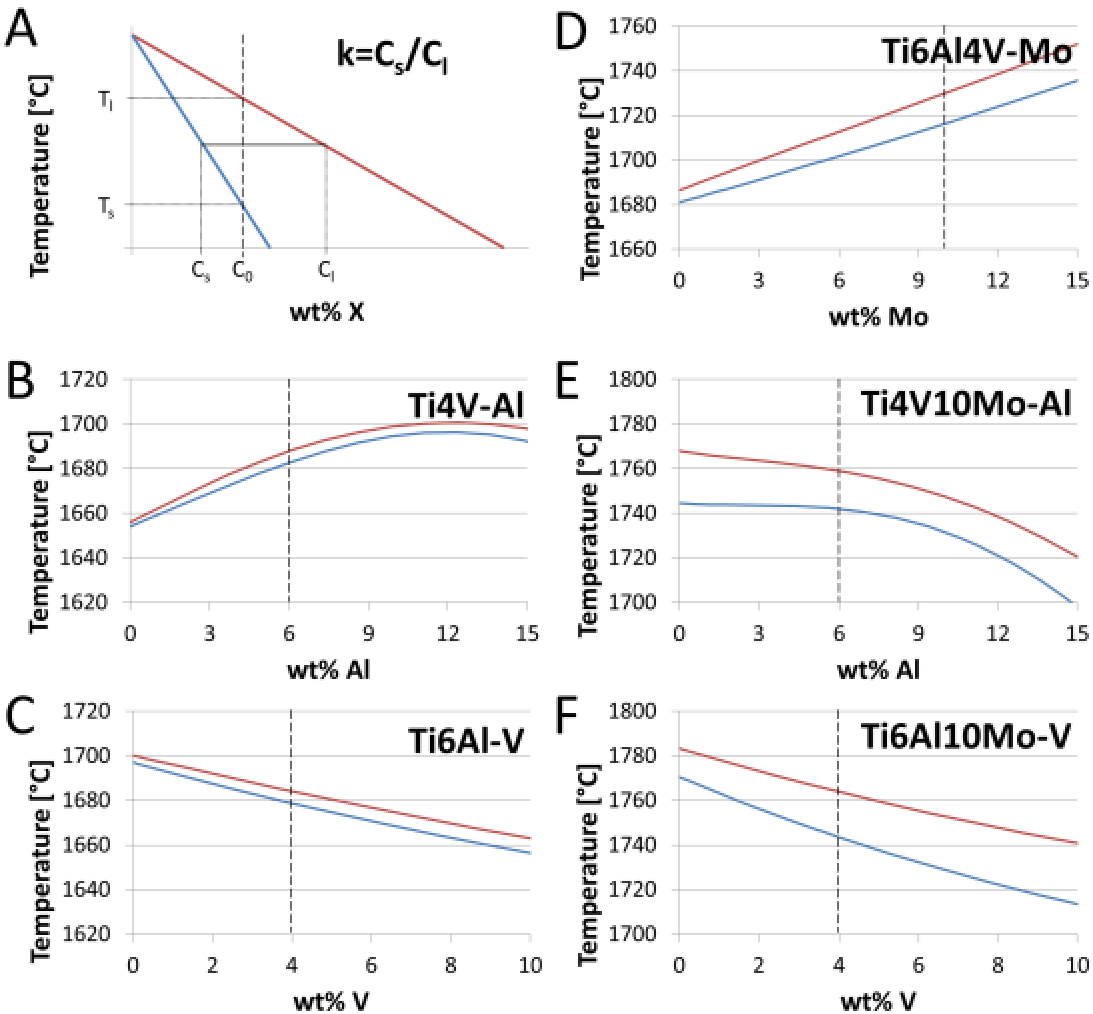


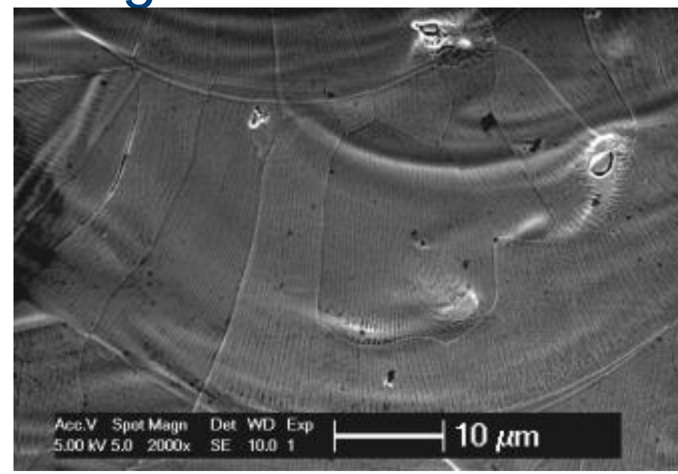
B. Vrancken, L. Thijs, J.P. Kruth, J. Van Humbeeck, “*Microstructure and mechanical properties of a novel beta titanium metallic composite by selective laser melting*”, Acta Mat, 68 (2014) 150-158

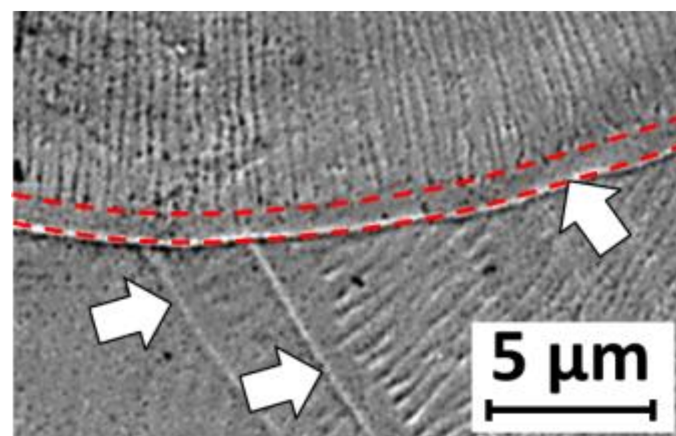
Ti6Al4V+10Mo: Change in solidification

- From planar to cellular mode

  →By changing the solidification range





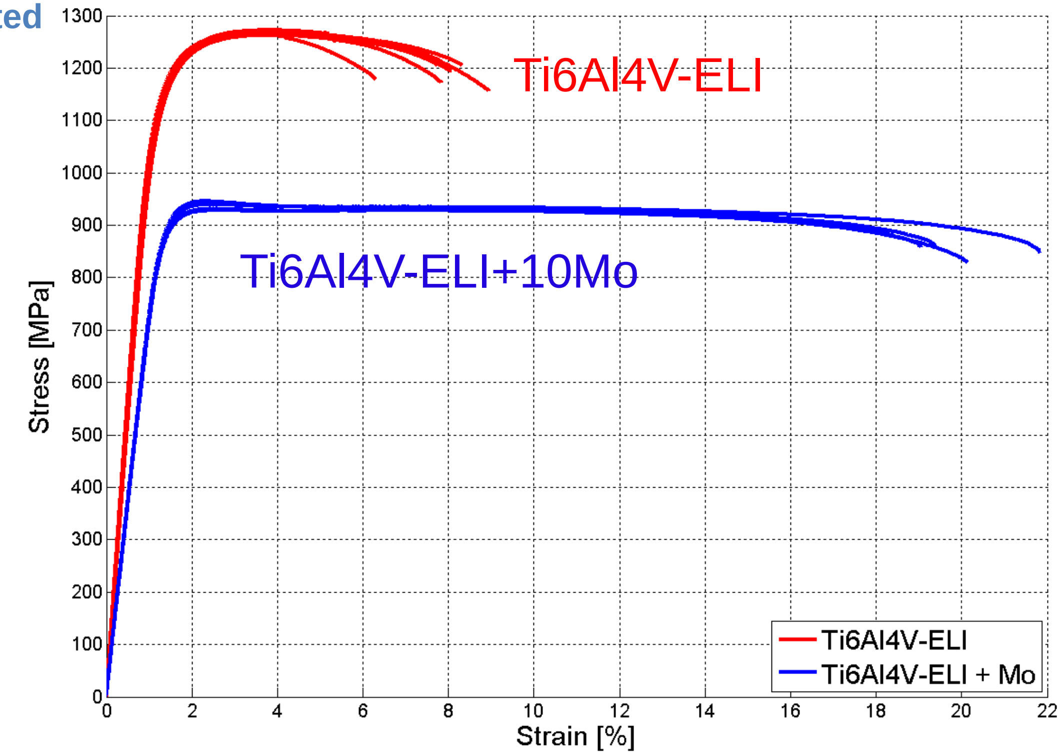


Ti6Al4V+10Mo: Increase in ductility

	Young's modulus E [GPa]	Yield Stress $\sigma_{0,2}$ [MPa]	UTS σ_{max} [MPa]	Fracture strain ε_{max} [%]	Source
Ti6Al4V (SLM)	109 ± 3	1110 ± 9	1267 ± 5	7,3 ± 1,1	
Ti6Al4V+10Mo	73 ± 1	858 ± 16	919 ± 10	20,1 ± 2,0	
Ti15Mo		483	690	20	ASTM F2066*
Ti12Mo6Zr2Fe		897	932	12	ASTM F1813**

(*) Bar, beta annealed (**) Solution treated

- High strength
- Excellent ductility
- Superior to other β Ti alloys



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Example 4: Scalmalloy: Al-4.5Mg-0.37 Zr-O.17Si-0.66Sc

(Sc: 0.3% maximal solubility)

Typical Values	Scalmalloy®	AlSi10Mg	TiAl6V4
0.2% Offset Strength (MPa)	450	210	860
Tensile Strength (Mpa)	490	350	910
Specific Strength	184	129	205
Elongation (%)	8	3	10
Vickers Hardness HV0,3	177	119	320
Fatigue Limit 3E7 cycles (MPa)	300	97	600
Density (g/cm^3)	2.67	2.70	4.43

Scalmalloy® ALM parts have properties in the range of high strength 5XX Al-Alloys

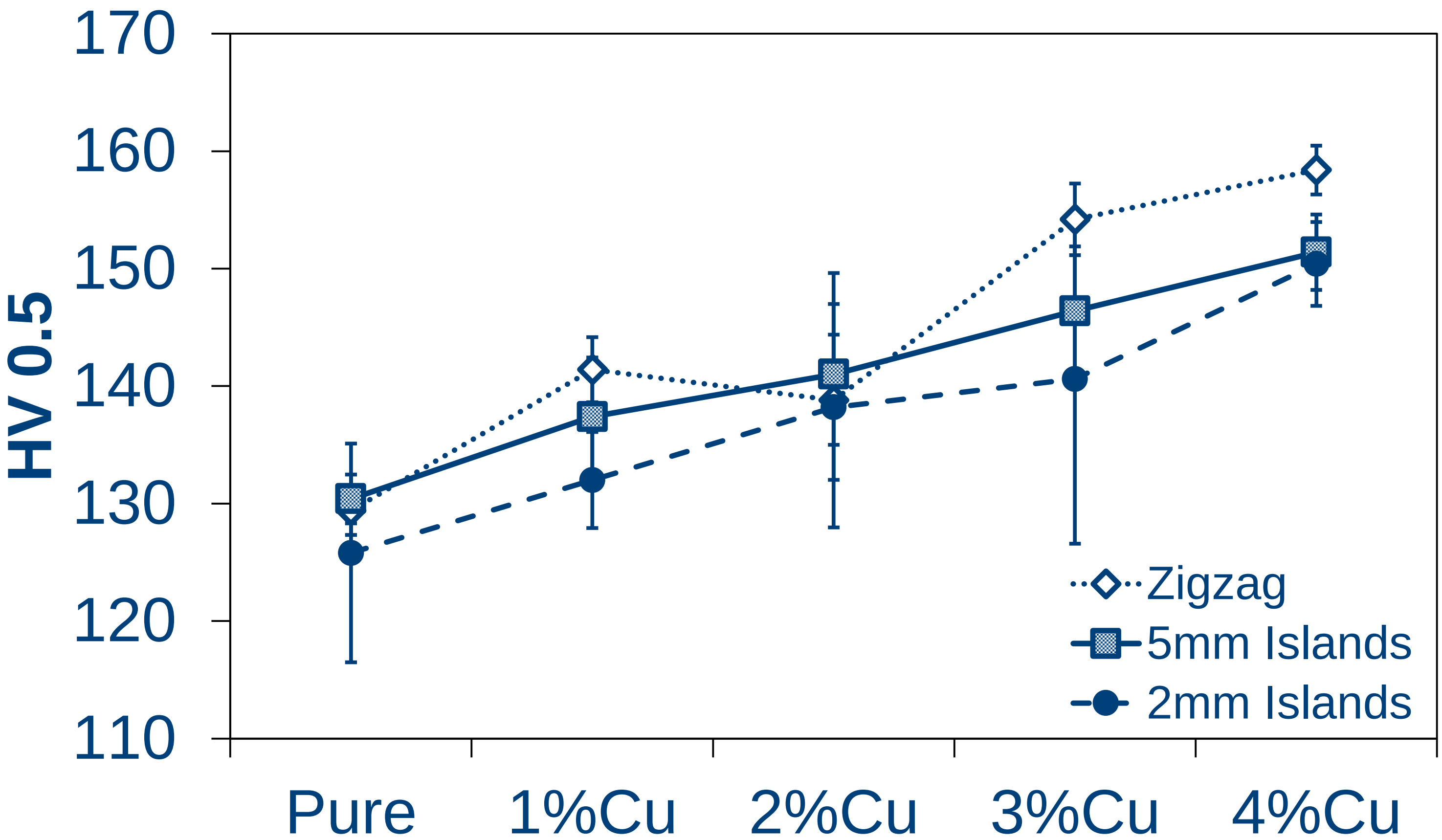
https://www.gtai.de/GTAI/Content/JP/Meta/Events/Reviews/jgif-2015/jgif15-zettler-7.pdf?v=2

K. Schmidtke, , F. Palm, A. Hawkins, C. Emmelmann , in Physics ProcediaVolume 12, Part A, 2011, Pages 369–374

Eric A. Jägle, Zhendong Sheng,Liang-Wu, Lin Lu, Jeroen Risse,3 Andreas Weisheit, Dierk Raabe,
JOM, Vol. 68, No. 3, 2016, p.943-949

Example 5: AlSi10Mg+Cu

- Strengthening by:
  - Solid solution
  - Formation of Guinier-Preston zones



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Example 6: Alumide

- Mix of polyamide and aluminium powder processed via SLS
  - 80 wt% PA + 20 wt% Al

- Shiny, rough appearance
- Much stiffer and slightly stronger than PA

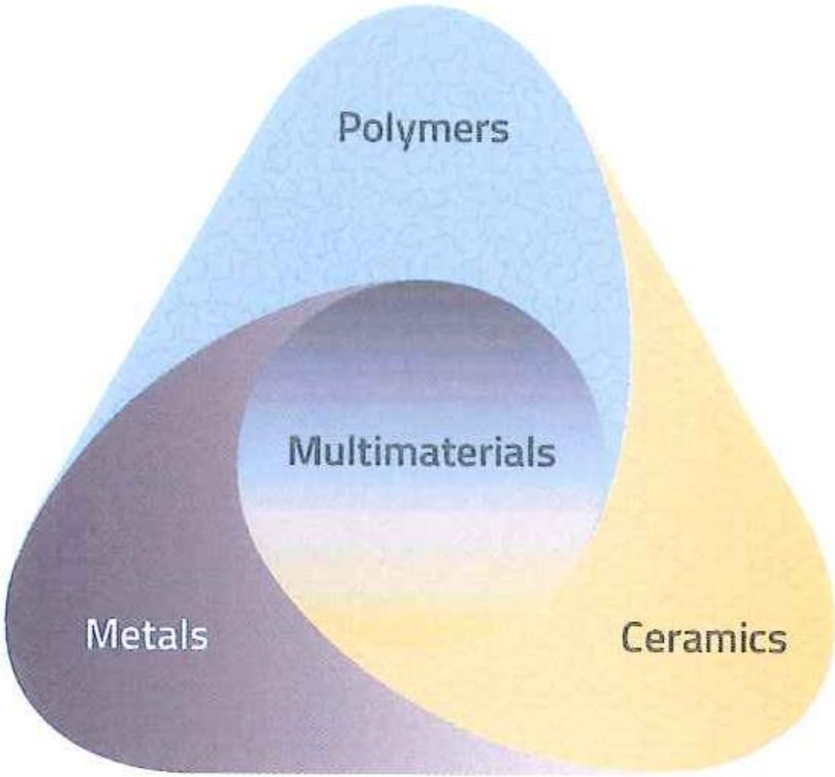
	E [GPa]	UTS [MPa]
Alumide	3,8	48
PA	1,7	45

i.materialise.com

Other examples

- Dongdong Gu, “Laser Additive Manufacturing of High-Performance Materials”,
  - Springer, 2015, ISBN 978-3-662-46088-7, 311pp.

Example 6= M+P+C?



3 Alloying to improve processability

Al7075: Mechanical properties

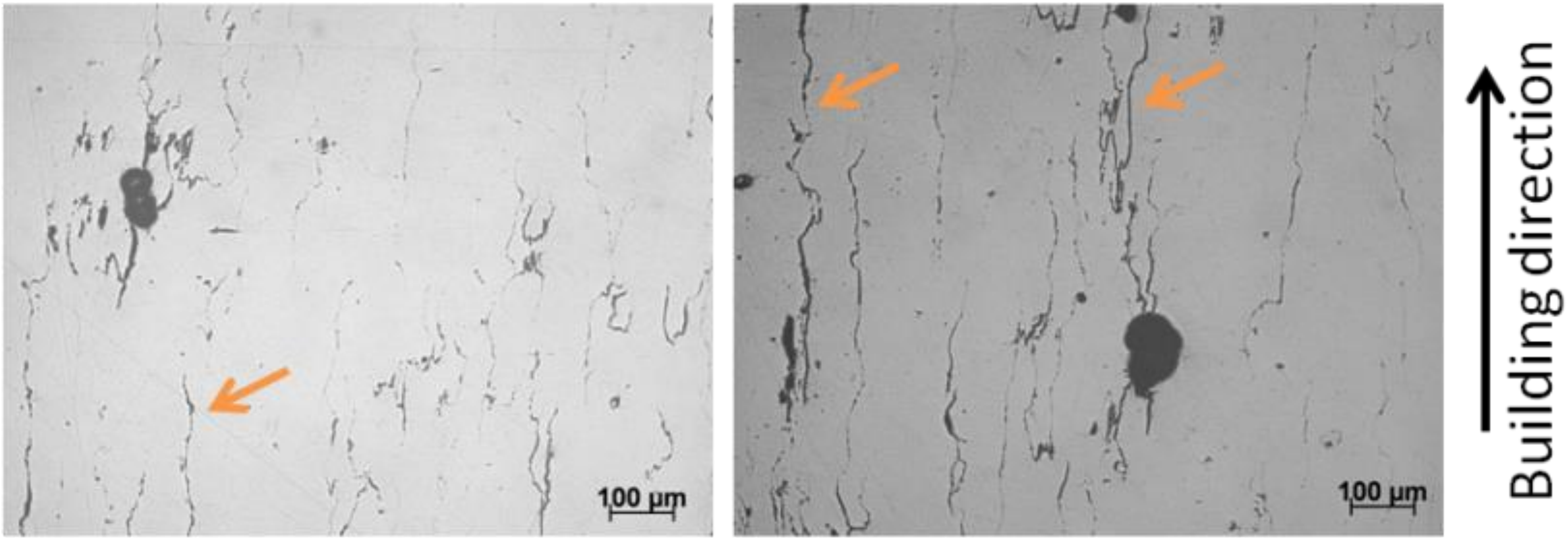
- Moderate to very high strength & tensile properties as-cast.
- High toughness → increased by nano intermetallic particles
- Natural aging
- Used in airframe structures, highly stressed parts…

	UTS [MPa]	YTS [Mpa]	Elongation at break [%]	Young's Modulus [Gpa]
Al7075-O	230	105	17	72
Al7075-T6,T651	570	505	11	72
AlSi10Mg T6	300-317	160-185	2.5-3.5	71
Al6061	120, 300	50, 265	25, 12	69
316L wrought	520-680	220-270	40-45	
Ti-6Al-4V	895	825	10	113.8

Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, volume 2, Chapter *Properties of Wrought Aluminum and Aluminum Alloys*, pages 62–120. ASM International, 1990.

Al7075: Problem Statement

- First attempt to build Al7075 with SLM
  - ✓ Max. Rel. density 95%
  - ✓ Many cracks



Al7075: Avoiding cracks

- Alloy composition

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other
AlSi12	11-13.5	<0.7	<0.1	<0.5	<0.1	-	<0.1	<0.15	Pb<0.1 Sn<0.05
AlSi10Mg	9-11	<0.6	<0.1	<0.6	0.15-0.40	-	<0.1	<0.2	Pb<0.1 Sn<0.05
Al6061	0.4-0.8	0.75	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	
Al7075	0.4	0.5	1.2-2	0.3	2.1-2.9	0.1-0.35	5.1-6.4	-	Ni 0.1

Improve fluidity and reduce thermal expansion coefficient.

Hardening phase Mg_2Si

No effect alone, but +Cu and +Mg→ natural aging or heat treatable

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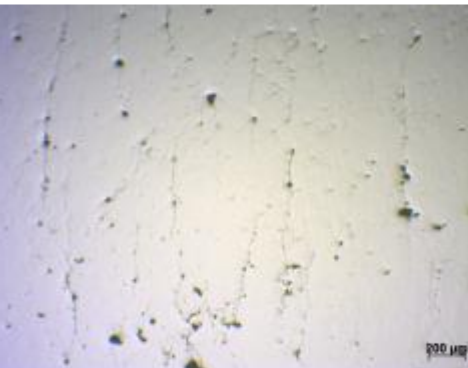
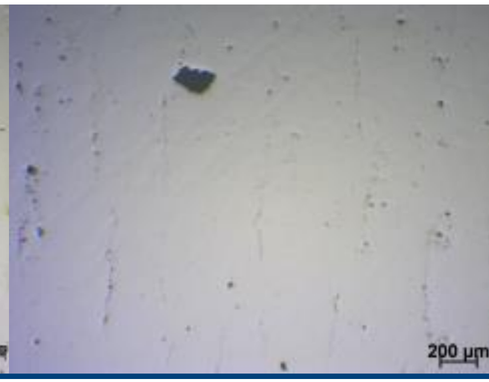
Al7075: Optimization of variables

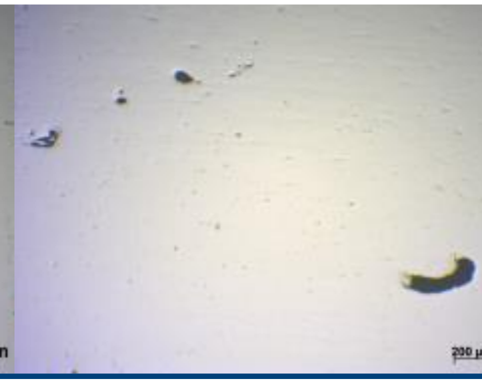
+1%Si



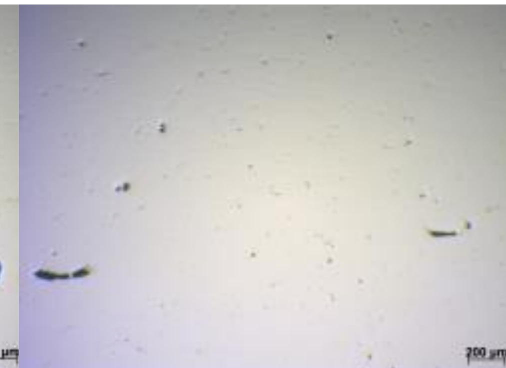
+2%Si



+3%Si



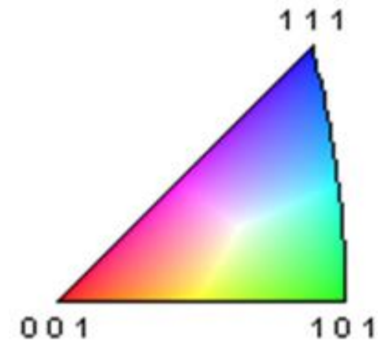
+4%Si



Density 94.5% 95.4% 98,8% 98.9%

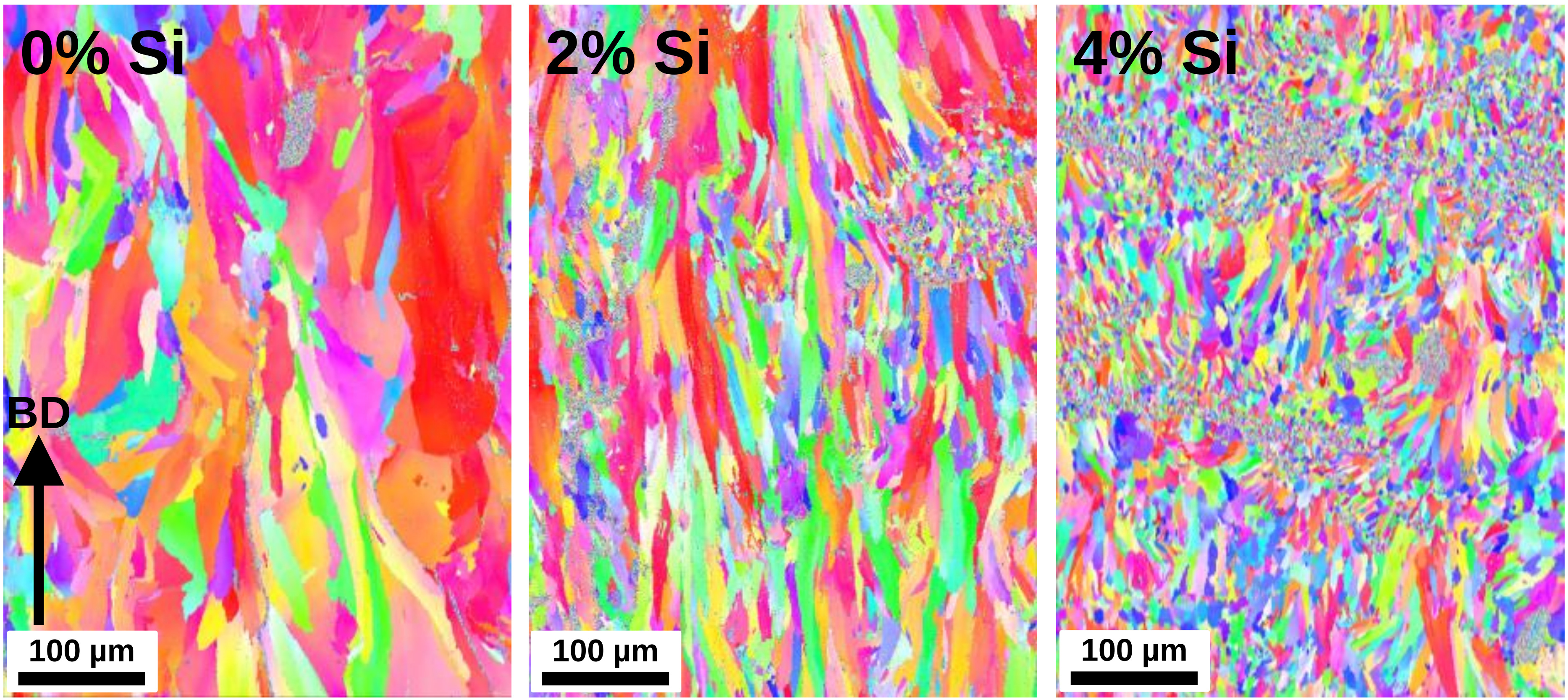
Optimal Parameters	
Laser Power [W]	300
Scan Speed [mm/s]	1000
Scan Spacing [µm]	110
Layer Thickness [µm]	30

Al7075: Microstructure



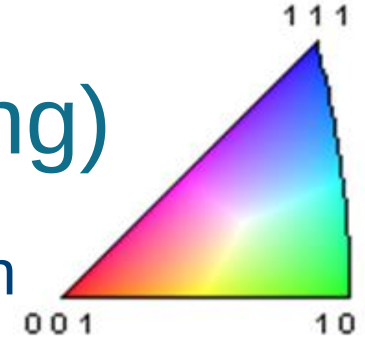
Grain refinement by addition of Silicon

Silicon inhomogeneously distributed: local ultrafine zones



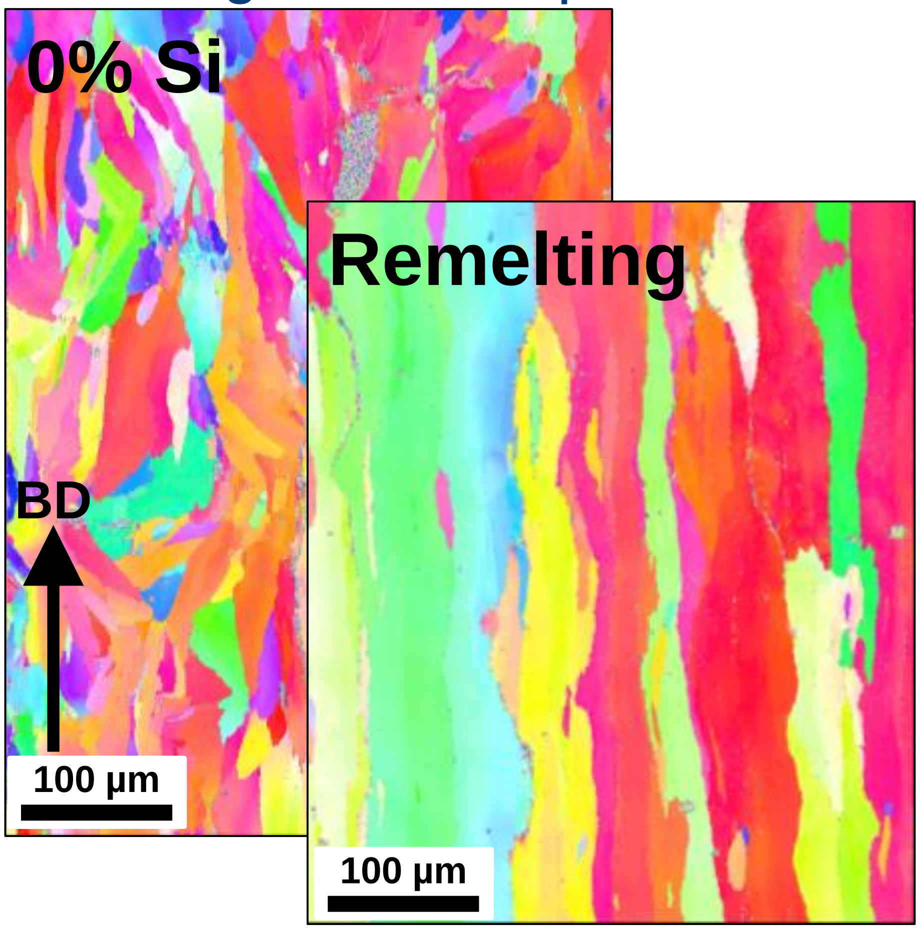
Images by Dr. Xiebin Wang

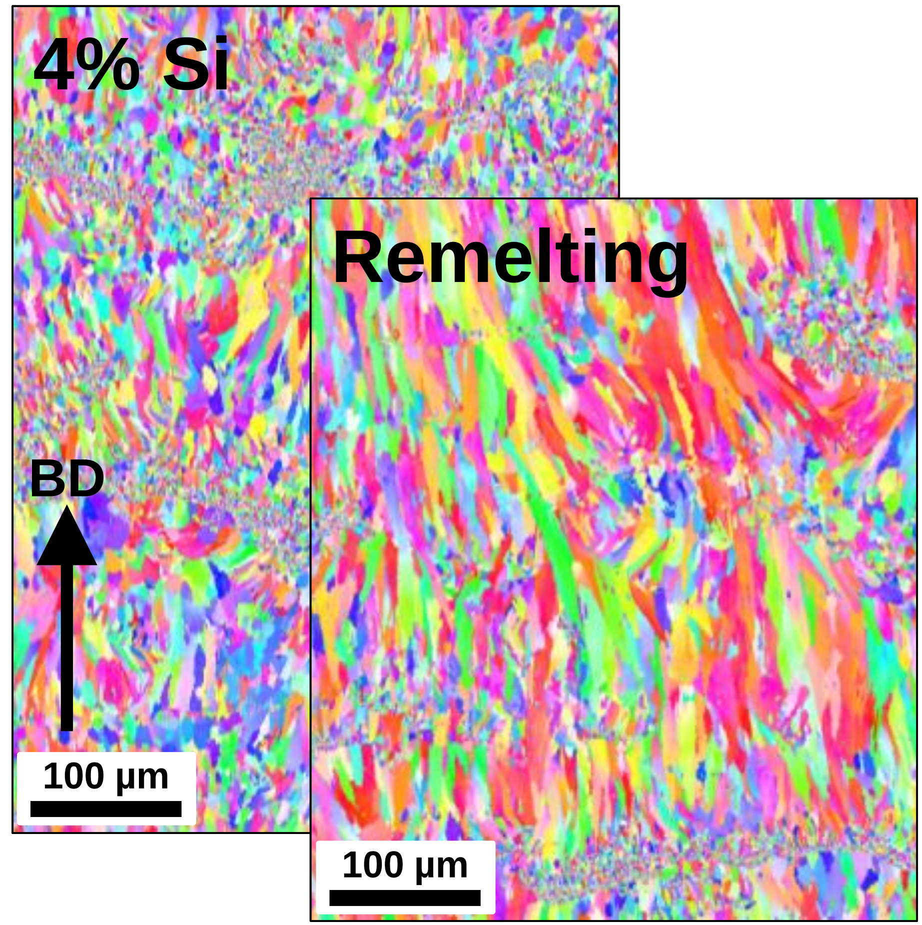
Al7075: Microstructure (Remelting)



Remelting is a second chance at epitaxial growth

Straighter crack path → More cracks





Images by Dr. Xiebin Wang

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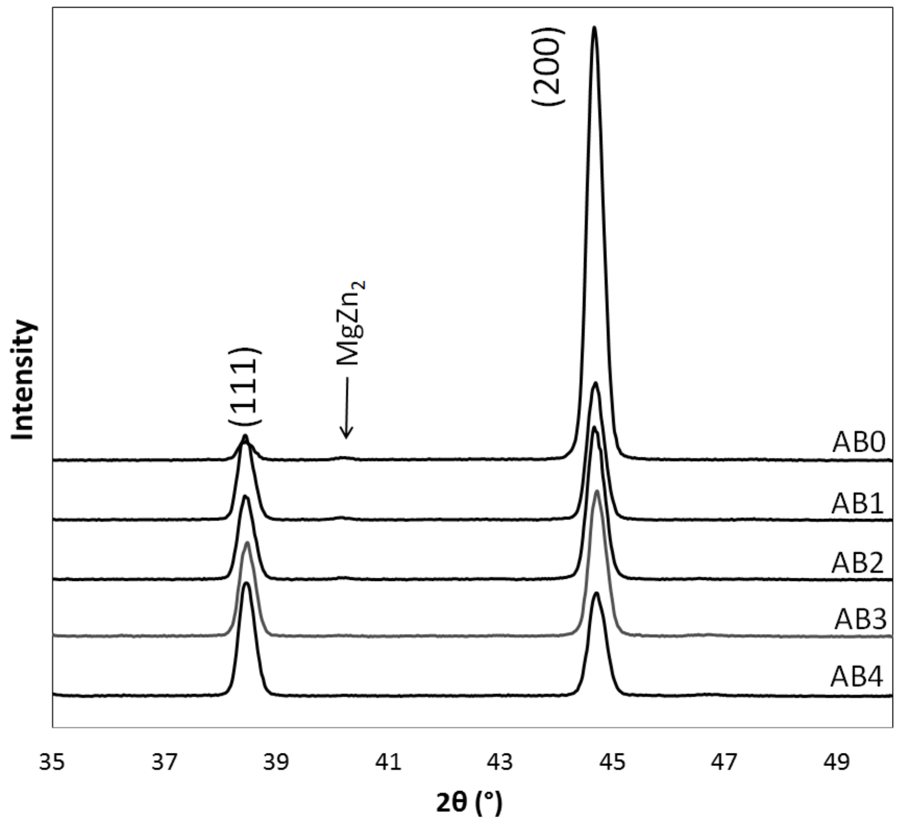
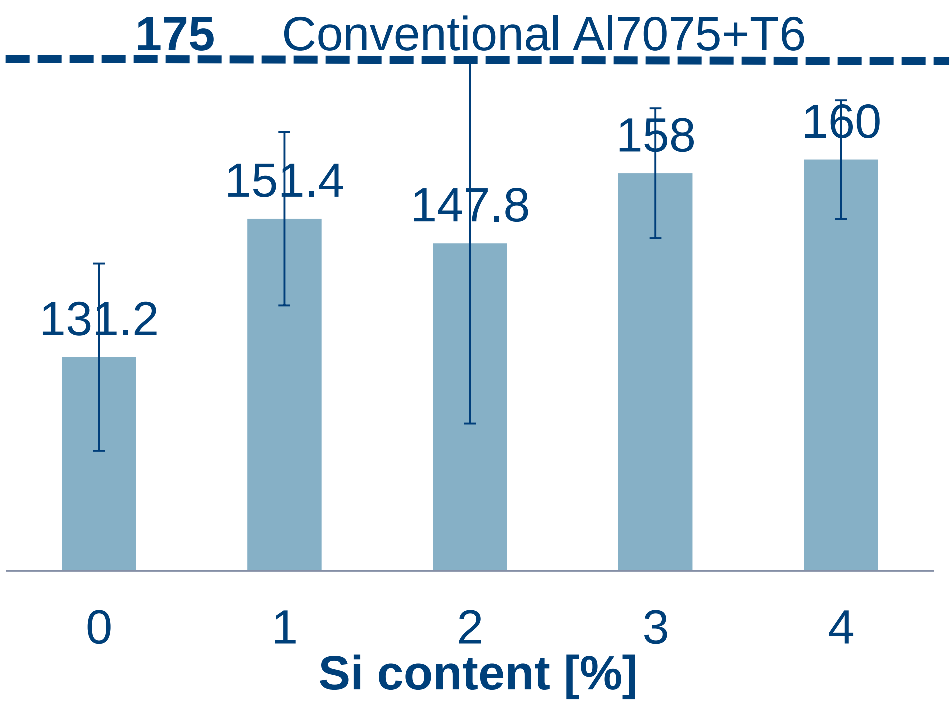
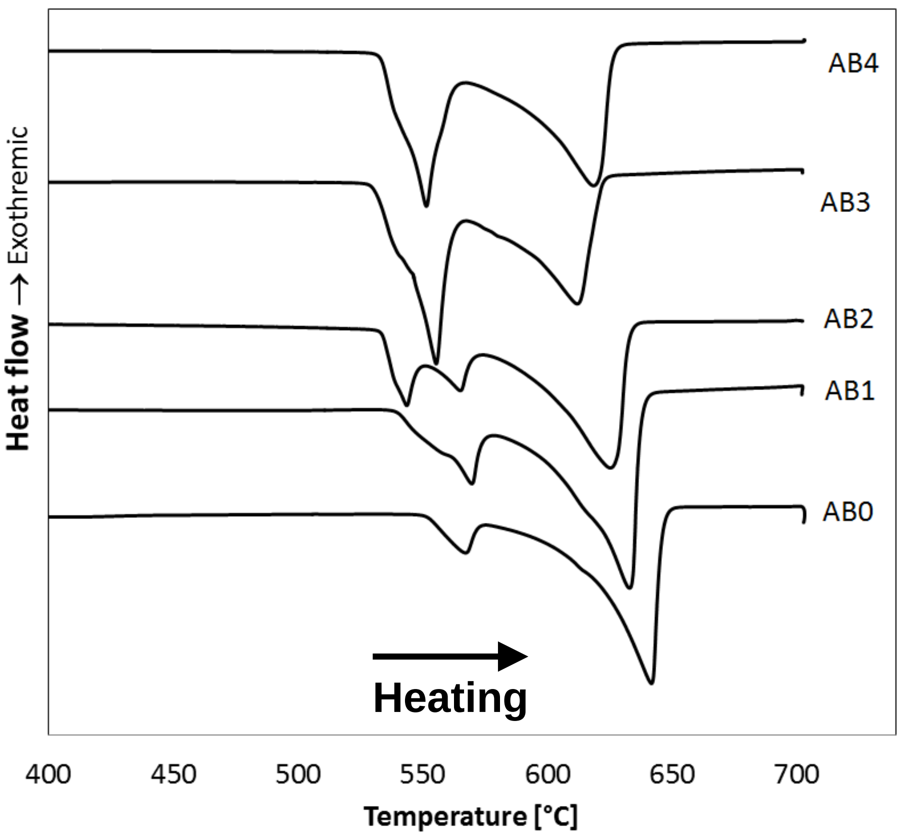
Al7075: Effect of Silicon

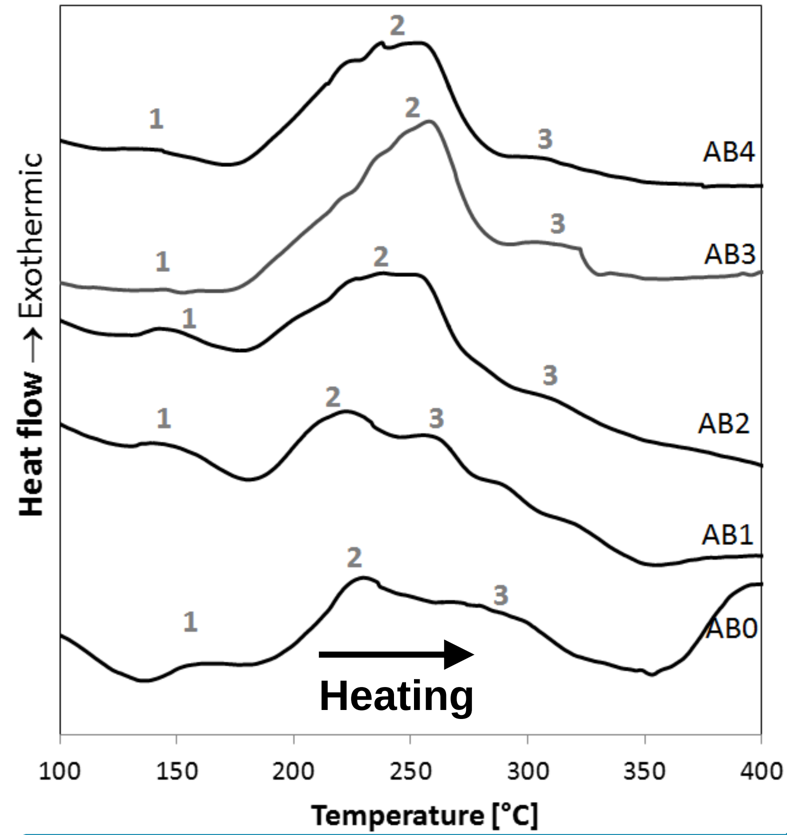
- Texture change when adding Si + small shift
- Hardness not lowered by Si addition
  - Up to 171 ± 4 $HV_{0,5}$ after aging at 150°C





Al7075: Effect of Silicon





↑ **Si%** → Tm ↓ and 2nd eutectics

↑ **Si%** → ↑ intensity and shifted → η and β precipitates

Al7075: Summary

Optimization

- **98.9% density**
- No remelting + island strategy
- +3% and +4%Si removes cracks

Effect of Si

- Reduces T_m and presence of low melting point phases
- **Microstructure grain refinement**

Hardness and HT

- **Si does not lower hardness**
- Comparable to conventional Al7075+T6
- **Tensile properties are not good**

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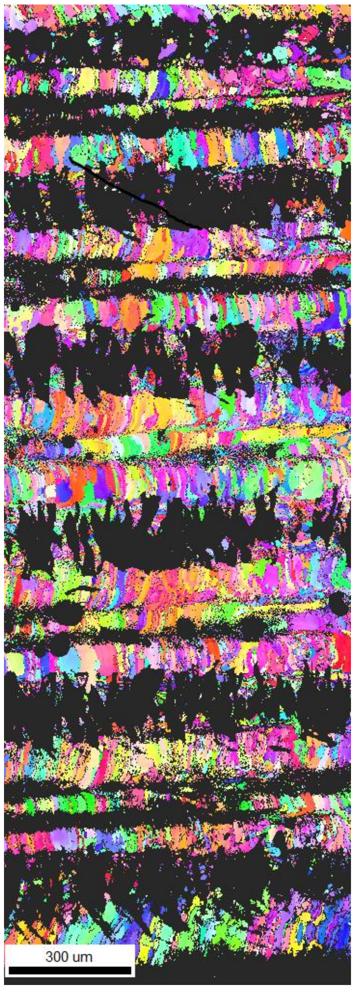
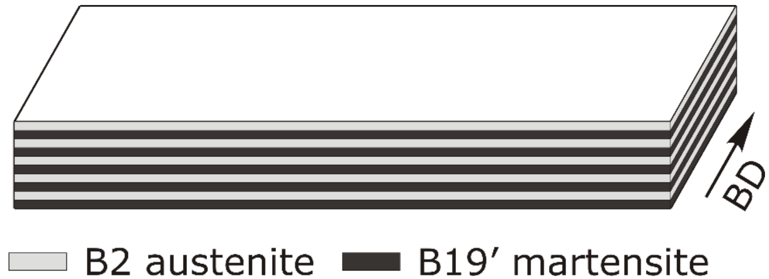
4

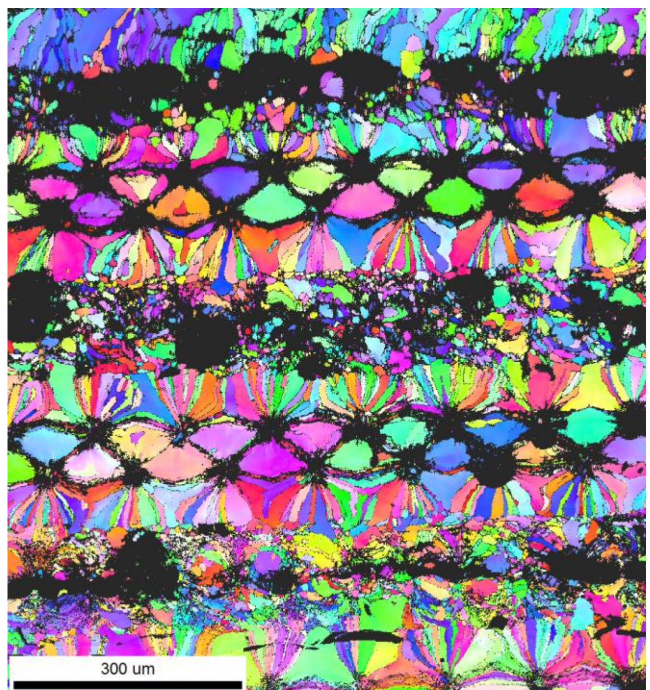
Different processing parameters for the same material

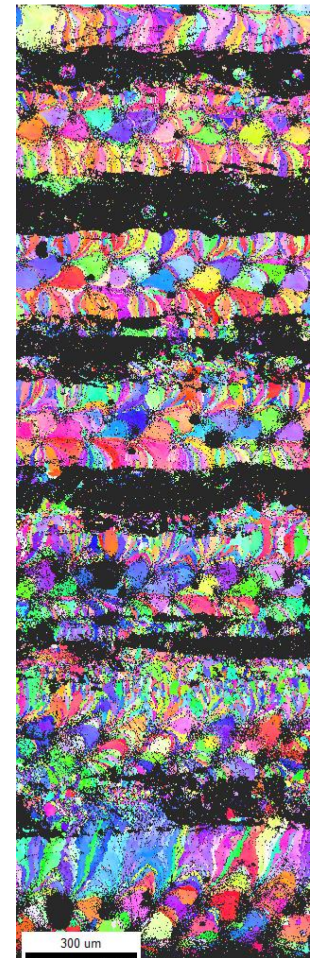
NiTi: martensite or beta depending on proces-parameters

LP: P = 40 W, v = 160 mm/s, h = 75 µm martensite (black area)
HP: P = 250 W, v = 1100 mm/s, h = 60 µm beta (coloured area

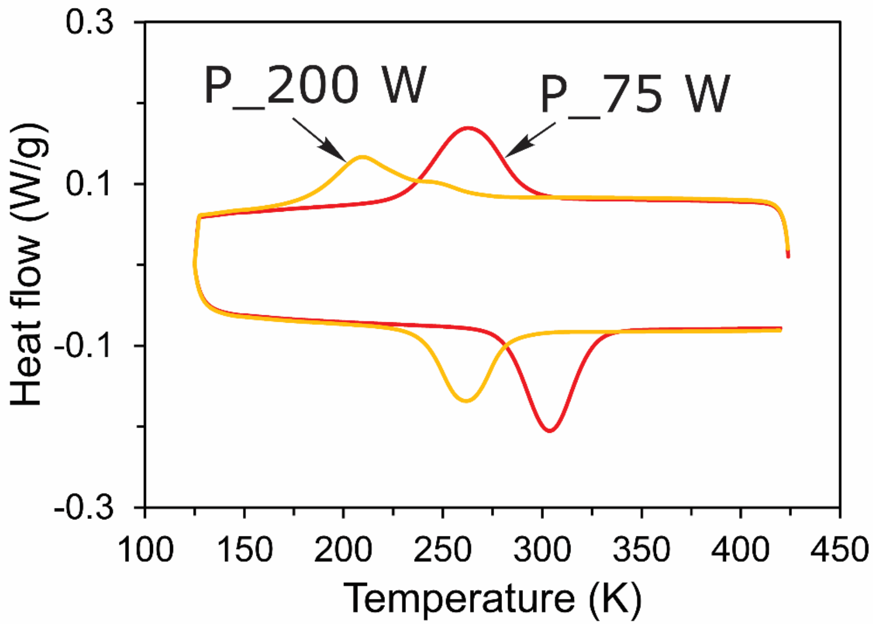




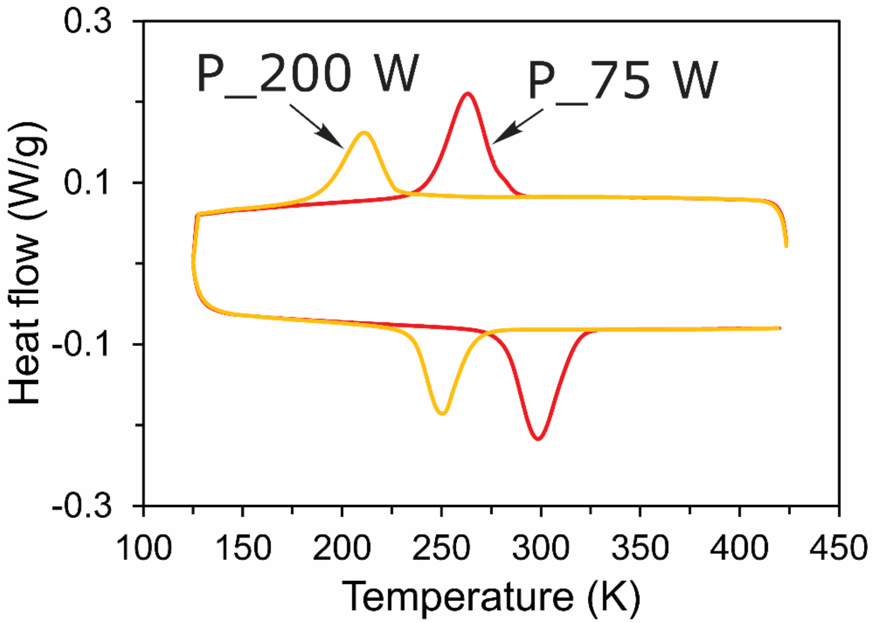




Layer-structured NiTi SMAs



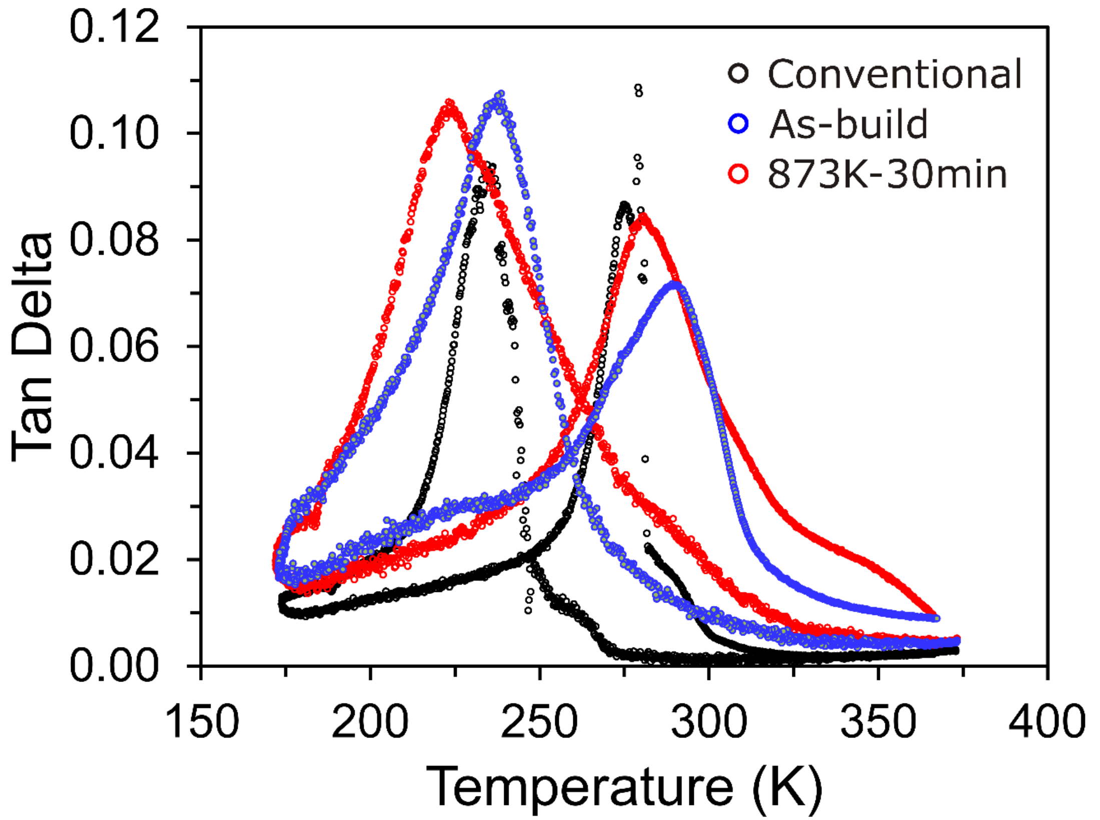
As-built



After annealing at 1273 K for 2 h

Layer-structured NiTi SMAs

Damping properties



Strain 3×10^{-5}; Frequency: 1Hz; Cooling/heating rate: 5 K/min

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Take home messages

Unique microstructures require bespoke heat treatments

The material composition should be tailored to the production process

Either by using elemental powders or alloy powder mixtures

The production process should be tailored to the material composition

You do not need to ask questions
but if you feel the need for it,
please do so!